

Apples

BOTANY, PRODUCTION AND USES

Edited by
D.C. Ferree and I.J. Warrington



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Apples

Botany, Production and Uses

The editors dedicate this book to all the professors, teachers, extension personnel, commercial growers and other professionals who willingly shared their knowledge, inspired their students and contributed to the extensive knowledge that is represented in this book.

Apples

Botany, Production and Uses

Edited by

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Preface

There is no fruit in temperate climates so universally esteemed, and so extensively cultivated, nor is there any which is so closely identified with the social habits of the human species as the apple.

(Dr Robert Hogg, *The Apple*, 1851)

Although the precise origin of today's apple is not entirely clear, it probably evolved from extensive forests of apples in central Asia, particularly in Kazakhstan. Due to its unique qualities, people collected and spread the most desirable types. Remains of apple have been reported in historic sites dated to 6500 BC. Long-distance trade routes between the Mediterranean area and various areas of Asia developed as early as 3500 BC and fostered the spread of both fresh and dried apples. Theophrastus (around 320 BC) studied apples brought back to Greece from conquests of Alexander the Great. He described grafting and general tree care and also dwarf types that later were used as rootstocks. Followers of both the Christian and Islam religions were instrumental in the spread of apples throughout Europe, Africa and the New World. By 1826, the Royal Horticultural Society of England had identified 1200 apple cultivars.

Commercial production of apples started as complements in gardens, as field borders or as overstorey trees in pastures. Apples are produced commercially in most countries in the temperate region of the world and also in some tropical areas with high altitude. In the last 100 years production has become increasingly intensified, with the use of dwarfing rootstocks and training systems designed to improve orchard efficiency. Apple is unique among fruit plants in having a range of rootstocks that permit development of a 'designer tree size' appropriate to the training system and management skills of modern orchardists.

In the last 50 years the development of herbicides, insecticides and fungicides has permitted the production of high-quality fruit in many areas where production was previously difficult. Currently, as more information is gained through research, the trend is to reduce pesticide inputs through integrated production systems or organic production. Apple breeders are assisting by developing high-quality cultivars with resistances to the most serious pests, through both conventional breeding and genetic engineering. Research in storage and postharvest handling techniques have dramatically improved fruit quality and currently apples are a quality product available throughout the year. Many of these current cultural practices are based on research results of detailed studies of the effects of various aspects of the environment on apple growth and development.

This book is an effort by 39 research scientists from eight countries to summarize the current research information on apples in a comprehensive treatise. Authors attempted to provide the information and physiology behind current cultural practices as well as future trends. The objective was to provide horticultural students, research and extension personnel, professional fruit growers and others with a comprehensive textbook on apples and their culture.

David C. Ferree
Ian J. Warrington

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1 Taxonomic Classification and Brief History

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1.1 The Origin and Spread of the Domesticated Apple

The common domesticated apple is putatively an interspecific hybrid complex, usually designated *Malus* × *domestica* Borkh. (Korban and Skirvin, 1984) or *M. domestica* Borkh. (Phipps *et al.*, 1990). Other synonyms, now considered illegitimate, have been applied, including *Pyrus malus* L., *Malus malus* Britt., *Malus pumila* Mill. and *Malus sylvestris* Mill. *M. × domestica* is now cultivated widely in temperate latitudes or at high elevations in the tropics on all continents except Antarctica. The fruits are eaten fresh, dried or tinned or processed into juice, preserves or alcoholic beverages. Besides *M. × domestica*, fruits of several other species are consumed fresh or processed or are used for medicinal purposes and the plants are used as rootstocks (Table 1.1). Many species and interspecific hybrids are used as ornamental plants.

The origin and ancestry of the *M. × domestica* complex remain unknown. Borkhausen, when first describing *M. × domestica* in 1803,

believed it originated as a hybrid derived from *M. sylvestris* Mill., *Malus dasycphyllus* Borkh. (a synonym for *M. pumila*) and *Malus praecox* Borkh. (a synonym for *M. sylvestris* var. *praecox* (Pall.) Ponomar.) (Korban and Skirvin, 1984). Currently, however, *Malus sieversii* (Ledeb.) Roem. is hypothesized as the key species in its origin (Ponomarenko, 1983; Vavilov, 1987; Roach, 1988; Way *et al.*, 1990; Hokanson *et al.*, 1997; Juniper *et al.*, 1998). *M. sieversii* is widespread in the mountains of central Asia at elevations between approximately 1200 and 1800 m. The forests are extensive and *M. sieversii* is the dominant overstorey species in many areas (Plate 1.1). The fruit of *M. sieversii* is highly variable (Plate 1.2) and individual trees resembling *M. × domestica* are commonly found in the forests of this region but their precise history is difficult to ascertain. Humans have inhabited and practised nomadic agriculture in this region for thousands of years. People of this region today will save desirable trees when the forest is cleared for agriculture (Ponomarenko, 1983).

Table 1.1. *Malus* species, synonyms and infraspecific classifications, from the taxonomy database of the US Department of Agriculture Germplasm Resources Information Network (USDA, ARS, National Genetic Resources Program Germplasm Resources Information Network (GRIN), 2000) and their chromosome number, presence of apomixis, distribution and uses (from GRIN and also Phipps *et al.*, 1990; Way *et al.*, 1990; Zhang *et al.*, 1993; Deng *et al.*, 1995; Schuster and Büttner 1995; Zhou, 1999)

Species	Chromosome number and apomixis (A)	Synonyms and infraspecific classifications and [putative origin of secondary species]	Distribution	Uses
Primary species				
<i>M. angustifolia</i> (Aiton) Michx.	34		Eastern USA	Ornamental, preserves
<i>M. baccata</i> (L.) Borkh	34, A	<i>M. baccata</i> var. <i>baccata</i> <i>M. rockii</i> Rehder <i>M. sibirica</i> (Maxim.) Kom., nom. illeg. <i>M. baccata</i> f. <i>gracilis</i> Rehder <i>M. baccata</i> f. <i>jackii</i> Rehder <i>M. baccata</i> subsp. <i>himalaica</i> (Maxim.) Likhonos <i>M. baccata</i> var. <i>himalaica</i> (Maxim.) C.K. Schneid. <i>M. baccata</i> var. <i>sibirica</i> C.K. Schneid.	North-eastern China, eastern Siberia, Mongolia, northern India, Bhutan, Nepal	Ornamental, rootstock
<i>M. baoshanensis</i> G.T. Deng			South-central China	Rootstock
<i>M. brevipes</i> (Rehder) Rehder	34		Only known in cultivation	Ornamental
<i>M. coronaria</i> (L.) Mill.	51, 68, A	<i>M. coronaria</i> var. <i>dasycalyx</i> Rehder <i>M. fragrans</i> Rehder <i>M. glabrata</i> Rehder <i>M. glaucescens</i> Rehder <i>M. lancifolia</i> Rehder <i>M. bracteata</i> Rehder	Eastern USA and Canada	Ornamental, fruit, preserves
<i>M. daochengensis</i> C.L. Li	—		South-central China	
<i>M. × domestica</i> Borkh	34, 51, 68, A	<i>M. malus</i> (L.) Britton, nom. inval <i>M. pumila</i> auct. <i>M. sylvestris</i> auct. <i>M. sylvestris</i> var. <i>domestica</i> (Borkh.) Mansf. <i>M. formosana</i> Kawak. & Kodz. <i>M. laosensis</i> (Cardot) A. Chev. <i>M. crataegifolia</i> (Savi) Koehne	Cultivated and naturalized in temperate regions	Fruit, preserves, beverage base, medicinal
<i>M. doumeri</i> (Bois) A. Chev			South-east China, Taiwan, South-east Asia	Preserves
<i>M. florentina</i> (Zuccagni) C.K. Schneid.	34		Turkey, Greece, Italy and Balkans	Ornamental

<i>M. floribunda</i> Siebold ex Van Houtte	34		Only known in cultivation	Ornamental
<i>M. fusca</i> (Raf.) C.K. Schneid.	34	<i>M. fusca</i> var. <i>diversifolia</i> (Bong.) C.K. Schneid. <i>M. rivularis</i> Douglas ex Hook. <i>M. diversifolia</i> (Bong.) M. Roem	Western USA and Canada	
<i>M. halliana</i> Koehne	34, 51		Central and eastern China, Japan	Ornamental, rootstock
<i>M. honanensis</i> Rehd.	—		North-central China	
<i>M. hupehensis</i> (Pamp.) Rehd.	34, 51, 68, A	<i>M. theifera</i> Rehd.	Central and south-east China	Ornamental, rootstock, fruit, beverage base, medicinal
<i>M. ioensis</i> (A.W. Wood) Britton	34, 51	<i>M. ioensis</i> var. <i>texana</i> Rehd.	Central USA	Ornamental, fruit
<i>M. jinxianensis</i> J.Q. Deng & J.Y. Hong	—		Northern China	
<i>M. kansuensis</i> (Batalin) C.K. Schneid.	34		Central China	
<i>M. komarovii</i> (Sarg.) Rehd.	—		North-east China	
<i>M. leiocalyca</i> S.Z. Huang	—		South-east China	
<i>M. maerkangensis</i> M.H. Cheng et al.	—		Central China	
<i>M. mandshurica</i> (Maxim.) Kom	34	<i>M. sachalinensis</i> Juz. <i>M. baccata</i> var. <i>cerasifera</i> (Spach) Koidz. <i>M. baccata</i> var. <i>mandshurica</i> (Maxim.) C.K. Schneid. <i>M. cerasifera</i> Spach <i>M. mandshurica</i> var. <i>sachalinensis</i> (Juz.) Ponomarev	Central and north-east China, far-eastern Russian, Japan	Rootstock
<i>M. melliana</i> (Hand.-Mazz.) Rehd.	—		South-east China	Fruit, beverage base
<i>M. micromalus</i> Makino	34, 51		Central and eastern China, Japan	Rootstock, fruit, medicinal
<i>M. muliensis</i> T.C. Ku	—		Central China	
<i>M. ombrophila</i> Hand.-Mazz.	—		South-central China	
<i>M. orientalis</i> Uglitzk.	—	<i>M. sylvestris</i> subsp. <i>orientalis</i> (Uglitzk.) Browicz	Caucasus, Iran	
<i>M. orthocarpa</i> Lavallee ex anon.	—	An uncertain taxon	Only known in cultivation	Ornamental
<i>M. prattii</i> (Hemsl.) C.K. Schneid.	34	<i>M. kaido</i> Dippel	Central China	Fruit

Continued

Table 1.1. Continued.

Species	Chromosome number and apomixis (A)	Synonyms and infraspecific classifications and [putative origin of secondary species]	Distribution	Uses
<i>M. prunifolia</i> (Willd.) Borkh.	34		Central and eastern China	Ornamental, rootstock
<i>M. pumila</i> Mill	34	<i>M. pumila</i> var. <i>niedzwetzkyana</i> (Dieck) C. K. Schneid. <i>M. sylvestris</i> var. <i>niedzwetzkyana</i> (Dieck) L. H. Bailey <i>M. niedzwetzkyana</i> Dieck <i>M. paradisiaca</i> (L.) Med. k. <i>M. dasyphylla</i> Borkh. <i>M. pumila</i> var. <i>paradisiaca</i> (L.) C. K. Schneid	Eastern Europe	Ornamental, rootstock
<i>M. sargentii</i> Rehder,	34, 51, 68, A		Only known in cultivation	Ornamental
<i>M. sieversii</i> (Ledeb.) M. Roem.		<i>M. sieversii</i> subsp. <i>turkmenorum</i> (Juz. & Popov) Likhonos <i>M. sieversii</i> var. <i>turkmenorum</i> (Juz. & Popov) Ponomar <i>M. sieversii</i> var. <i>kirghisorum</i> (Al. Fed. & Fed.) Ponomar <i>M. kirghisorum</i> Al. Fed. & Fed. <i>M. turkmenorum</i> Juz. & Popov	Central Asia	Rootstock, fruit, preserves
<i>M. sikkimensis</i> (Wenz.) Koehne ex C. K. Schneid.	51, A		South-central China, northern India, Bhutan	Rootstock, ornamental
<i>M. spectabilis</i> (Aiton) Borkh.	34, 51		Eastern China	Ornamental
<i>M. sylvestris</i> Mill.		<i>M. praecox</i> (Pall.) Borkh. <i>M. sylvestris</i> var. <i>praecox</i> (Pall.) Ponomar	Europe	Ornamental, fruit, preserves
<i>M. torii</i> (Siebold) Siebold ex de Vries	34, 51, A	<i>M. sieboldii</i> (Regei) Rehder <i>M. sieboldii</i> var. <i>arborescens</i> Rehder	Eastern China, Japan, Korea	Ornamental, rootstock
<i>M. toringoides</i> (Rehder) Hughes	51, 68, A	<i>M. transitoria</i> var. <i>toringoides</i> Rehder	Central China	Rootstock
<i>M. transitoria</i> (Batalin) C. K. Schneid.	34, 51		North central China	Rootstock
<i>M. tschonoskii</i> (Maxim.) C. K. Schneid.	34		Japan	

<i>M. xiaojinensis</i> M H. Cheng & N.G. Jiang			Central China	Rootstock
<i>M. yunnanensis</i> (Franch.) C.K. Schneid.	34	<i>M. yunnanensis</i> var. <i>veitchii</i> (Veitch) Rehder	South-central China	Ornamental, rootstock
<i>M. zumi</i> (Matsum.) Rehder	34	<i>M. yunnanensis</i> var. <i>yunnanensis</i>		
		<i>M. zumi</i> var. <i>calocarpa</i> (Rehder) Rehder	Japan	
		<i>M. sieboldii</i> var. <i>calocarpa</i> Rehder		
<i>Docynia indica</i> (Wall.) Decne.		<i>M. docynioides</i> C K. Schneid.	Eastern Himalayas, south-east Asia	
<i>Eriolobus trilobata</i> (Poir.) M. Roem	34	<i>M. trilobata</i> (Poir.) C K. Schneid	Eastern Mediterranean	
Secondary species				
<i>M. × adstringens</i> Zabel	34, 51	[= <i>M. baccata</i> × <i>M. pumila</i>]	Only cultivated	Ornamental
<i>M. × arnoldiana</i> (Rehder) Sarg. ex Rehder	34	[= <i>M. baccata</i> × <i>M. floribunda</i>]	Only cultivated	Ornamental
<i>M. × asiatica</i> Nakai		<i>M. floribunda</i> var. <i>arnoldiana</i> Rehder		
		[= <i>M. prunifolia</i> × <i>M. sieversii</i>]	Cultivated in east Asia	Rootstock, fruit, preserves
		<i>M. prunifolia</i> var. <i>ninkii</i> (Koz.) Rehder		
		<i>M. ringo</i> Siebold ex Carriere		
<i>M. × astracantha</i> hort. ex Dum. Cours.		[= <i>M. prunifolia</i> × <i>M. pumila</i>]	Only cultivated	Ornamental
<i>M. × atrosanguinea</i> (Spath) C K. Schneid.		[= <i>M. halliana</i> × <i>M. tonngo</i>]	Only cultivated	Ornamental
<i>M. × dawsoniana</i> Rehder	34	[= <i>M. domestica</i> × <i>M. fusca</i>]	Only cultivated	Ornamental
<i>M. × hartwigii</i> Koehne	34	[= <i>M. baccata</i> × <i>M. halliana</i>]	Only cultivated	Ornamental
<i>M. × magdeburgensis</i> Hartwig		[= <i>M. pumila</i> × <i>M. spectabilis</i>]	Only cultivated	Ornamental
<i>M. × moerlandsii</i> Door.	34	[= <i>M. × purpurea</i> 'Lemoinei' × <i>M. tonngo</i>]	Only cultivated	Ornamental
<i>M. × platycarpa</i> Rehder	51, 68, A	[= <i>M. domestica</i> × <i>M. coronaria</i>]	Eastern North America	
<i>M. × purpurea</i> (E. Barbier) Rehder	34	[= <i>M. astrosanguinea</i> × <i>M. pumila</i> 'Niedzwetzkyana']	Only cultivated	Ornamental
		<i>M. × purpurea</i> f. <i>eleyi</i> (Bean) Rehder [= <i>M. × purpurea</i> 'Eleyi' (<i>M. astrosanguinea</i> × <i>M. pumila</i> 'Niedzwetzkyana')]		
		<i>M. floribunda</i> var. <i>lemoinei</i> E. Lemoine [= <i>M. × purpurea</i> 'Lemoinei']		
		<i>M. × purpurea</i> f. <i>lemoinei</i> (E. Lemoine) Rehder [= <i>M. × purpurea</i> 'Lemoinei']		
		<i>M. × purpurea</i> var. <i>aldenhamensis</i> Rehder [= <i>M. × purpurea</i> 'Aldenhamensis']		

Continued

Table 1.1. Continued

Species	Chromosome number and apomixis (A)	Synonyms and infraspecific classifications and [putative origin of secondary species]	Distribution	Uses
<i>M. × robusta</i> (Carriere) Rehder	34	[= <i>M. baccata</i> × <i>M. prunifolia</i>]	China, cultivated	Ornamental, rootstock
<i>M. × scheideckeri</i> Spath ex Zabel	—	[= <i>M. floribunda</i> × <i>M. prunifolia</i>]	Only cultivated	Ornamental
<i>M. × soulardii</i> (L.H. Bailey) Britton	34	[= <i>M. ioensis</i> × <i>M. pumila</i>]	Centra. USA, naturalized and cultivated	Fruit, ornamental
<i>M. × sublobata</i> (Dippel) Rehder	—	[= <i>M. prunifolia</i> × <i>M. torngo</i>]	Only cultivated	Ornamental

and will commonly graft and plant desirable *M. sieversii* from the forest in their gardens. Planting desirable trees from root suckers may also have been a common practice prior to, or in addition to, grafting, as *M. sieversii* trees sucker freely. Conversely, people may have cloned and moved some of their horticulturally desirable trees to areas where they seasonally grazed their animals. These trees or their open-pollinated descendants may be among the horticulturally elite specimens observed in some of the forests today.

The passage of trade routes from China to the Middle East and Europe through Central Asia probably facilitated repeated short- and long-distance dispersal to the east and west, either intentionally or unintentionally, of *M. sieversii* and its hybrid derivatives. The *M. × domestica* complex may then have arisen through hybridization to the east with species native to China, including *Malus prunifolia* (Willd.) Borkh., *Malus baccata* (L.) Borkh., *Malus mandshurica* (Maxim.) Kom. and *Malus sieboldii* (Regel) Rehder. To the west, hybridization with the local species *M. sylvestris* and *Malus orientalis* Uglitzk. is conjectured (Ponomarenko, 1983; Morgan and Richards, 1993; Hokanson *et al.*, 1997; Juniper *et al.*, 1998).

During the late 19th and 20th centuries, *M. × domestica* cultivars found or bred in Europe, Russia, North America, New Zealand, Japan and Australia were introduced throughout the world and form the basis for most current commercial apple production (Way *et al.*, 1990; Janick *et al.*, 1996). Several species are known to have contributed to the *M. × domestica* complex in modern breeding programmes including *Malus floribunda* Siebold ex Van Houtte, *Malus micromalus* Makino, *Malus × atrosanguinea* (Spath) C.K. Schneid., *M. baccata*, *Malus zumi* (Matsum.) Rehder and *Malus sargentii* Rehder (Ponomarenko, 1983; Way *et al.*, 1990; Janick *et al.*, 1996).

In southern and eastern Asia, the Chinese soft apple, *Malus asiatica* Nakai, was the primary cultivated apple in China and surrounding areas for over 2000 years until *M. × domestica* was introduced in the late 19th and early 20th centuries (Morgan and Richards, 1993; Zhang *et al.*, 1993; Watkins,

1995; Zhou, 1999). *Malus × asiatica* is probably a hybrid complex derived primarily from *M. sieversii* with *M. prunifolia* and perhaps other species.

Prehistoric remains and historical records, reviewed by Morgan and Richards (1993), provide evidence of the cultivation, dispersal and human use of the apple in Asia and Europe over the last several thousand years. Archaeological remains of apple that dated to about 6500 BC were found in Anatolia, though it is impossible to know the source of this fruit or whether it was cultivated. Historical evidence referring to apple cultivation dates to the second millennium BC from Anatolia and northern Mesopotamia. By 500 BC, the apple was probably cultivated widely throughout the Persian Empire, as fruit orchards feature prominently in writings from the period. When Alexander the Great conquered the Persians around 300 BC, the cultivation of fruits was dispersed through the Greek world. By this time, the Greek philosopher, Theophrastus, had distinguished the sweet cultivated apple from astringent wild forms.

The ascendancy of the Roman Empire spread cultivation of the domesticated apple north and west through Europe, where it supplanted and probably hybridized with the native crab apple, *M. sylvestris*. Multiple varieties were recorded by the Roman writer Pliny, and they had attained an important place in Roman cuisine, medicine and aesthetics by the 1st century AD. The Roman goddess Pomona was revered as the deity associated with apple and other fruits. With the rise and spread of Christianity and Islam over the next several centuries, apples were carefully maintained, even through wars and difficult times, in the abbey gardens throughout Europe and the orchards of Iberia. These apparently replaced the native crab apples, which had a place in the diet of early Celts, Gauls, Franks, Scandinavians and other peoples of northern Europe in fermented, dried or cooked forms. Maintenance of fruit gardens was encouraged as a basic monastic skill and many abbeys developed large orchards with many *M. × domestica* cultivars. Likewise in the Muslim world of the eastern Mediterranean and Iberia, fruit growing was

revered in keeping with Koranic teachings and skills of grafting, training and pruning became highly developed.

From the 13th century, apples became more and more widely planted throughout Europe in gardens of royalty and commoners. Raw apples were occasionally consumed, but they were more greatly prized when cooked and sometimes blended with spices and sugar or honey. Fermented juice, or cider, like beer, was preferred to the sometimes questionable local water-supply. By the 17th century there were at least 120 cultivars described in western Europe. The rise and spread of Protestantism, which saw the apple as the special fruit of God, is credited with expanding apple cultivation across northern and eastern Europe after beginning in Germany in the early 17th century. By the end of the 18th century, many hundreds of cultivars were recognized throughout Europe. The Royal Horticultural Society of England acknowledged at least 1200 in 1826. The 18th and 19th centuries saw apple cultivars recognized and classified based on their suitability for their end uses (Plate 1.3). Aromatic dessert apples were more widely appreciated by this time, while good cooking types were still appreciated for puddings and pastries (Plate 1.4). Flavourful cultivars with moderate acid and tannin levels were prized for cider production. The late 19th and early 20th centuries represented the maximum of diversity in apple cultivation in Europe, with hundreds of locally popular cultivars being grown in thousands of small orchards (Plates 1.5 and 1.6). In the 20th century, the rise of imported fruit from the Americas, New Zealand (Plate 1.7), Australia and South Africa (Plate 1.8) forced European orchards to increase in size and decrease in number and, to a large extent, to adopt the very same cultivars that were developed in and imported from the New World.

Apples were established in the 1650s near Cape Town in South Africa to sustain settlers and to supply the ships of the Dutch East India Company. The commercial apple orchard district in the Western Cape was started by Cecil Rhodes and his associates in the late 19th and early 20th century to replace a faltering wine industry.

Apples were introduced to Australia, on the island of Tasmania and at the present site of Sydney, in 1788. Orchards were established by settlers in Tasmania and New South Wales by the early 1800s. Significant production areas were eventually developed in Tasmania and the south-eastern mainland. In 1814, English missionaries brought apples from Australia to New Zealand, where two large apple-production districts became established in the districts of Hawke's Bay and Nelson during the 19th and 20th centuries.

Beginning in the 16th and 17th centuries, European colonists brought apples to the Americas. Spanish priests introduced them to their missions in Chile and California. Spanish and Portuguese settlers introduced apples to their settlements in suitable temperate climate zones of South America. European settlers brought apple seeds to establish orchards in the eastern USA and Canada. Apples grew well from northern Georgia to eastern Canada and, as in Europe, were soon highly prized for food and drink and as a source of sugar and alcohol. The first orchards in New England were recorded in the 1620s and 1630s and became important components of the New England farmstead (Plate 1.9). Likewise, they became important on the large plantations of the mid-Atlantic colonies by the mid-1700s, including those of the early US presidents George Washington and Thomas Jefferson. Jefferson, an astute horticulturist, acquired and carefully tested dozens of cultivars for his Monticello gardens in Virginia.

In Canada, French colonists established orchards in the 17th century along the St Lawrence valley. Settlers also established orchards around Lake Ontario and in the milder valleys of Nova Scotia and New Brunswick.

As settlers moved westward in the USA, apple orchards were a requirement of homesteading throughout the territories of the Ohio River valley. Jonathan Chapman, known as Johnny Appleseed (Fig. 1.1), devoted his later life, from 1806 to 1847, to helping settlers establish thousands of apple trees on their new farms in the Ohio River drainage. The Great Lakes region of the USA,



JOHNNY APPLESEED

Fig. 1.1. Only known drawing of Jonathan Chapman, 'Johnny Appleseed', supplied by Johnny Appleseed Heritage Center, Inc.

especially the states of New York, Michigan and Ohio, continues to be a major apple-production area.

In 1847, as settlers moved into the productive valleys of western Oregon, Washington and northern California, Henderson Llewelling brought 700 trees with his family on the Oregon Trail and eventually established the first fruit nursery in the Pacific Northwest. As irrigation schemes were eventually developed, the Pacific Northwest, especially including the basin of the Columbia River and its tributaries west of the Cascade Mountains and extending to the Okanagon River valley in British Columbia, eventually became one of the pre-eminent apple-production areas of the world (Plate 1.10).

By the early 20th century, the USA and Canada were the two largest apple-producing

nations. Later in the century, the USSR also became important. By the beginning of the 21st century, China has become the largest apple producer, with a large proportion of the crop being exported as concentrated juice (Plate 1.11). Major southern-hemisphere production, much of it for export to northern-hemisphere countries during their spring and summer, occurs in South Africa, Chile, Argentina, New Zealand and Australia. Production is currently dominated by strains of just a few cultivars: 'Delicious', 'Golden Delicious', 'McIntosh' and 'Jonagold' developed in North America; 'Braeburn' and 'Gala' from New Zealand; 'Granny Smith' from Australia; and 'Fuji' from Japan. Though many other cultivars remain locally important, these dominate current production and are also widely used in breeding programmes around the world.

From its origins among the millions of wild *M. sieversii* trees in the mountains of central Asia and from the early development of thousands of local cultivars in Europe and America, the domesticated apple, as cultivated in the 21st century, has shrunk drastically in diversity.

1.2 Taxonomy and Evolution

1.2.1 Apples in the family *Rosaceae*

Apples are members of the genus *Malus* Miller, which is placed in the subfamily *Maloideae* of the family *Rosaceae* (Fig. 1.2). Other members of the *Maloideae* that are cultivated for their fruit include pears (*Pyrus* L. spp.), quinces (*Cydonia oblonga* Mill.), loquats (*Eriobotrya japonica* (Thunb.) Mill.), medlars (*Mespilus germanica* L.) and species of *Amelanchier*, *Aronia*, *Crataegus* and *Sorbus*. The subfamily *Maloideae* is one of four in the family *Rosaceae*. The other subfamilies are *Rosoideae*, *Spiroideae* and *Amygdaloideae*. The circumscription of these subfamilies has defied general agreement among systematists, depending on whether classification schemes emphasize morphological traits, chromosome numbers, intergeneric crossability or molecular polymorphisms (Rohrer *et al.*, 1991, 1994; Morgan *et al.*, 1994). The *Maloideae*

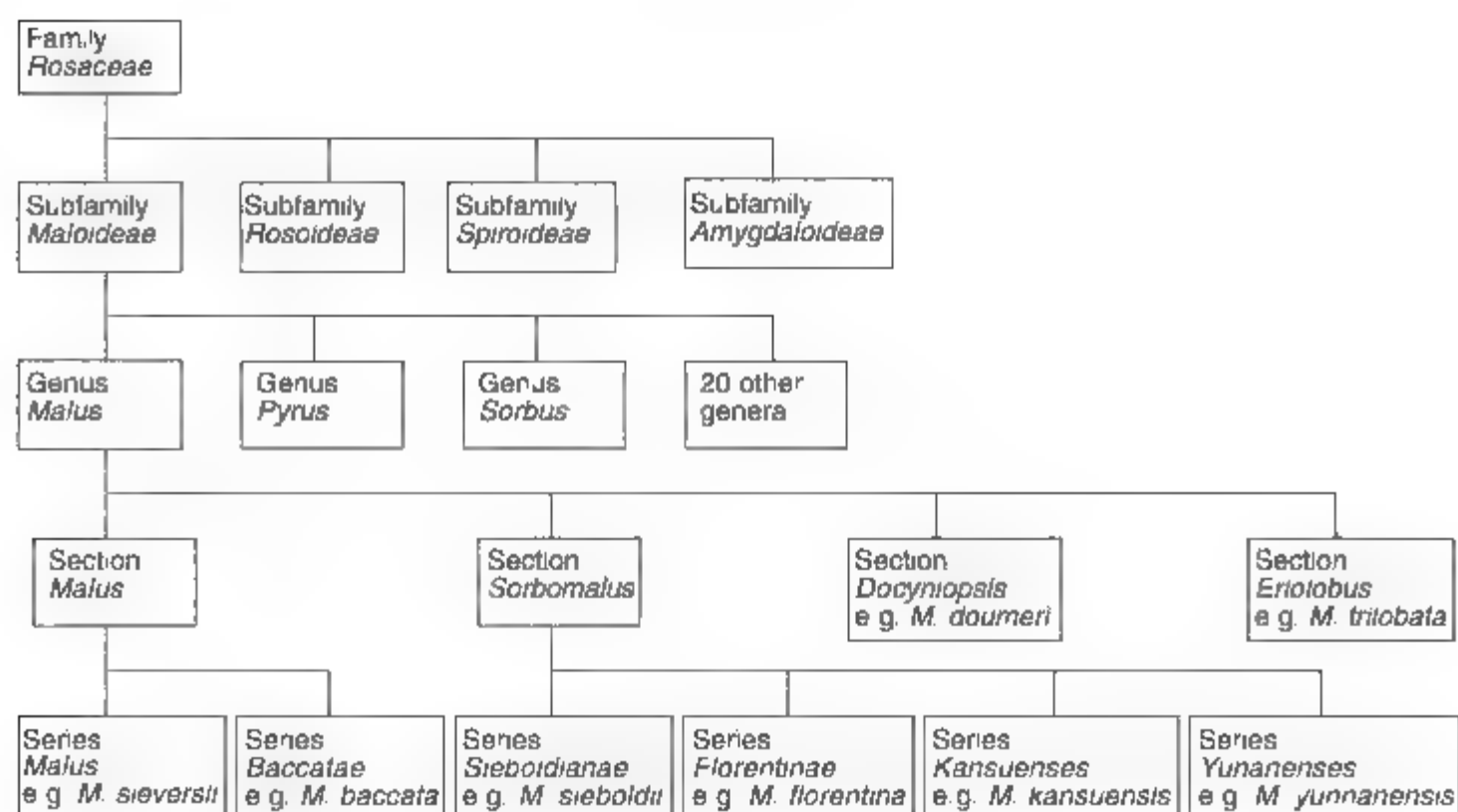


Fig. 1.2. Taxonomy of *Malus* (adapted from Phipps *et al.*, 1991).

are characterized by a hypanthium and gynoecium that remain fused to form an inferior ovary that develops into a fleshy, indehiscent fruit, or pome. Some genera with capsules or follicles, however, are apparently more closely related to genera in the *Maloideae* than to genera in other subfamilies, based on DNA sequence variation (Morgan *et al.*, 1994).

The subfamily *Maloideae* has a high haploid base chromosome number of $x = 17$ and is generally considered to be monophyletic when morphological traits, chromosome number (Kalkman, 1988; Phipps *et al.*, 1991) and DNA sequence variation from the chloroplast *rbcL* gene (Morgan *et al.*, 1994) and S-RNase (self-incompatibility) gene (Ushijima *et al.*, 1998) are considered. Data from nuclear ribosomal DNA sequences, however, support a single phylogeny for most of the genera, including *Malus*, but a separate phylogeny for the genera *Eriobotrya*, *Rhaphiolepis* and *Vauquelinia* (sometimes placed in the *Spiroroideae*) (Campbell *et al.*, 1995).

Based on cytology and analysis of morphological characters, the *Maloideae* probably have a polyploid origin (Phipps *et al.*, 1991). Isozyme studies in *Malus* support an allopolyploid origin, based on the presence of duplicated gene systems, allele segregations and fixed heterozygosities (Chevreau *et*

al., 1985; Weeden and Lamb, 1987; Dickson *et al.*, 1991). An allotetraploid origin involving ancestral *Spiroroideae* (mostly $x = 9$) and *Amygdaloideae* ($x = 7$) was proposed by Sax (1931, 1933) and is supported by flavonoid chemistry (Challice, 1974; Challice and Kovanda, 1981) and morphological traits (Phipps *et al.*, 1991). DNA sequence variation in the *rbcL* chloroplast gene suggests that *Amygdaloideae* and *Maloideae* are both advanced groups that arose from $x = 9$ spiraeoid-like ancestors (Morgan *et al.*, 1994). Data from internal transcribed spacer regions of nuclear ribosomal DNA genes are less comprehensive but support *Spiraea* as a closer relative to the *Maloideae* than *Rosa* or *Prunus* (Campbell *et al.*, 1995).

The taxonomic treatment of genera within *Maloideae* has varied from five cited in Linnaeus's original treatment up to 33 (Robertson *et al.*, 1991). Varying morphology and numerous instances of intergeneric hybridization complicate delimitation of genera. Robertson *et al.* (1991) describe 28 genera, including *Malus*. Species currently included in *Malus* were included in *Pyrus* by Linnaeus and others until the mid- to late 19th century. Campbell *et al.* (1995) considered molecular, morphological and wood anatomical data in determining relationships among genera.

Parsimony analyses of nuclear ribosomal DNA sequence variation placed *Malus* close to *Heteromeles*, *Chaenomeles*, *Photinia*, *Cydonia* and *Pyrus*. A numerical taxonomic treatment of morphological and wood anatomical studies placed *Malus* in a cluster that includes *Crataegus*, *Mespilus*, *Amelanchier*, *Peraphyllum* and *Rhaphuolepis*. A parsimony analysis, with both morphological and molecular data pooled, placed *Malus* close to *Chaenomeles*, *Pyrus* and *Aria*.

1.2.2 Species in the genus *Malus*

The delimitation of species within *Malus* has been problematic, with various treatments recognizing from as few as eight to as many as 78 primary species (Ponomarenko, 1986; Phipps *et al.*, 1990). Many hybrid species, derived naturally or artificially, are recognized (Phipps *et al.*, 1990; Way *et al.*, 1990). Many of the commonly described primary species and hybrid derivatives are listed in Table 1.1. The classification and species retained here are consistent with the taxonomy database of the US Department of Agriculture Germplasm Resources Information Network (USDA, ARS, National Genetic Resources Program, Germplasm Resources Information Network (GRIN), 2000) at <http://www.ars-grin.gov> on the World Wide Web. A primary centre of species richness and diversity is in south-west China, with several species ranging east to Manchuria and Japan and others extending to western Europe. A secondary centre exists in North America, with four native species.

The species of *Malus* have been arranged in varying numbers of sections or subgenera, some of which are, in turn, divided into series (Fig. 1.2). Most recent authors modify the treatment of Rehder (1940) and assign *Malus* species to five sections of the genus based on morphological traits and flavonoid similarities (Phipps *et al.*, 1990):

1. Section *Malus*, consisting of series *Malus*, including many European and Asian species (including *M. sieversii* and *M. × domestica*), with fruit having five carpels and mostly

persistent calyces on the fruit, and series *Baccatae*, containing several Asian species, with fruit consisting of three to five carpels and deciduous calyces.

2. Section *Sorbomalus*, including series *Sieboldianae*, with species native to Japan, series *Florentinae*, with *Malus florentina* (Zuccagni) C.K. Schneid. from south-east Europe, series *Kansuenses*, containing small-fruited Chinese species (and the North American *Malus fusca* (Raf.) C.K. Schneid.), with deciduous calyces and persistent fruit, and series *Yunnanenses*, species from China with persistent calyces and generally persistent fruit.

3. Section *Eriolobus*, containing only *Malus eriolobus* (Poir.) C.K. Schneid. from the eastern Mediterranean.

4. Section *Choromeles*, containing exclusively North American species.

5. Section *Docyniopsis*, containing the species *Malus tschonoskii* (Maxim.) C.K. Schneid., *Malus doumeri* (Bois) A. Chev., *Malus melliana* (Hand.-Mazz.) Rehder and *Malus formosana* Kawak. & Koidz. of Japan, Taiwan and South-East Asia.

Robertson *et al.* (1991) revised the genera in *Maloideae* based primarily on a comprehensive numerical taxonomic treatment of 115 morphological traits, including foliage, inflorescence and fruit by Phipps *et al.* (1991). In the genus *Malus*, they retained three subgenera: (i) *Malus*; (ii) *Sorbomalus*; and (iii) *Chloromeles*. Several former *Malus* species are placed in other genera: *Eriolobus* includes *E. trilobata* (Poir.) M. Roem. (= *Malus trilobata*) and *Docyniopsis* includes *D. tschonoskii* (Wall.) Decne. (= *M. tschonoskii*) and presumably would include *M. doumeri*, *M. formosana* and *M. melliana*. They suggested that further work may support inclusion of the genus *Docyniopsis* as part of the genus *Docynia* and elevation of subgenus *Chloromeles* to genus.

The difficulty in species delimitation in *Malus* arises from the great diversity, potential for hybridization and polyploidy and presence of apomixis in the genus (Campbell *et al.*, 1991). These phenomena may be indicative of a fairly recently derived genus in which species have developed rapidly through adaptive radiation and are primarily

isolated by geography. Genetic barriers are not well developed, as putative natural hybrids are common and artificial interspecific hybrids are easily produced (Korban, 1986; Way *et al.*, 1990). Molecular polymorphisms have been used to identify affinity and phylogeny among taxa in *Malus*. At the molecular level, many relationships are similar to those based on traditional classifications. Nevertheless, some anomalous relationships remain problematic, even at the DNA level. In many studies, the lack of resolution may be due to limited sampling where only one accession is used to represent a taxon. In addition, the veracity of a wild species accession may be questionable if it was obtained as seed from a botanic garden or even in native sites occupied by multiple *Malus* species or in close proximity to domesticated apple trees.

The occurrence of various flavonoids in *Malus* species (Williams, 1982) was in general agreement with relationships established by morphology except that *M. florentina* showed greater affinity with species in section *Docyniopsis* than in *Sorbomalus*, where Rehder (1940) placed it. A phylogenetic analysis based on chloroplast DNA restriction-site polymorphisms identified three lineages (Matsumoto *et al.*, 1997). One included only species in section *Malus* of the genus, including *M. asiatica*, *M. baccata*, *M. mandshurica*, *M. sargentii*, *Malus prattii*, *Malus transitoria* and *Malus toringoides*. A second included *M. pumila* and *M. prunifolia* from section *Malus*, but also included *M. tschonoskii* from section *Docyniopsis*. The third group included the species *Malus angustifolia* (Aiton) Michx. and *Malus ioensis* (A.W. Wood) Britton of the North American section *Chloromeles* but also included *Malus yunnanensis* (Franch.) C.K. Schneid. and *M. florentina* of section *Sorbomalus*, and even *Eriolobus trilobata* (= *M. trilobata* of section *Eriolobus*).

Restriction-site polymorphisms in mitochondrial DNA from 14 genotypes yielded 11 haplotypes and further illustrated the confusion in relating molecular data to conventional classifications (Kato *et al.*, 1993). The 12 accessions from section *Malus* accounted for nine distinct haplotypes. The *M. × domes-*

tica cultivars 'Golden Delicious', 'McIntosh' and 'Delicious' each had a different haplotype. One accession of *Malus micromalus* shared its haplotype with two accessions of *M. baccata*, but the other two accessions of *M. micromalus* each had a novel haplotype, one of which was shared with *M. floribunda*.

Several researchers have attempted to determine relationships among *Malus* species or accessions using DNA polymorphisms generated by the polymerase chain reaction using either primers with random sequences (random amplified polymorphic DNA, RAPD) or primers that specifically amplify DNA in segments containing multiple repeats of simple base motifs (simple sequence repeat, SSR). Dunemann *et al.* (1994) examined RAPDs in 27 *M. × domestica* cultivars and in 18 accessions of other species and found that they supported the close relationship of *M. × domestica* with *M. pumila* and *M. sylvestris* and the distance of section *Malus* species from *M. ioensis* in section *Chloromeles* and *E. trilobata* (= *M. trilobata*). RAPDs observed by Zhou and Li (2000) and Oraguzie *et al.* (2001) support the close relationship of *M. sieversii*, *M. prunifolia* and *M. sylvestris* with *M. × domestica* and a slightly more distant relationship with *M. orientalis* and *M. baccata*. Observing SSR polymorphisms among 142 species and hybrid accessions, Hokanson *et al.* (2000) deduced that accessions of *M. fusca* formed a distinct group, as did accessions of North American section *Chloromeles* species, *M. ioensis*, *Malus coronaria* and *M. angustifolia*. Beyond these groupings, SSR markers were not useful in establishing species relationships or phylogeny.

The initial analyses of molecular data, described above, provide only minimal additional insights into relationships and phylogeny beyond those suggested by classical analyses based on morphological traits. Although more sophisticated molecular analyses may provide more precision in the future, high resolution may still be quite difficult to obtain, especially among the many Eurasian species in section *Malus*, where divergence may have been relatively recent, enforced primarily by isolation or obscured by hybridization.

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2 World Production, Trade, Consumption and Economic Outlook for Apples

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2.1 Introduction

Apples grow readily throughout temperate climatic zones. However, commercial apple production is increasingly concentrated in countries and in growing districts that have a strong comparative advantage in apple production and marketing. Falling trade barriers have meant that it has become increasingly difficult for less efficient producers to find shelter from more efficient external competitors. The development of more heat-tolerant cultivars, the increasing popularity of varieties that require a long growing season (such as 'Granny Smith'

and 'Fuji') and advances in irrigation technology have permitted apple production to expand successfully into warmer climates (O'Rourke, 1994).

2.2 Apple Production Trends

World apple production has been on a long-term growth trend since the Second World War. The rate of growth slowed in the 1980s, but leaped ahead in the 1990s, due to just one factor, the phenomenal expansion of production in China. At the beginning of the 1990s, Chinese apple pro-

duction was about 4 million t. By the end of the decade it had grown more than five-fold. China has provided all the increase in acreage of apples harvested around the world since the mid-1980s (Fig. 2.1). In the 1990s, apple acreage harvested in the rest of the world has been declining (O'Rourke, 2000).

Production increases in most countries have resulted primarily from more intensive production methods, rather than from any significant net increases in planted area. Orchards have become fewer and larger. Producers have concentrated production on large, level blocks on valley floors rather than persisting with smaller, more difficult hillside blocks.

Apple production has been static or declining in many countries of both Europe and the former Soviet Union in the last decade as traditional plantings have been exposed to competitive realities (FAO, a). It has been rising modestly in North America over this same period and at a brisk pace in southern hemisphere producing countries. Improvements in transportation, relatively weak exchange rates and the demand of supermarkets for year-round supplies have given southern hemisphere producers an incentive to expand production.

However, even in Europe, apple production has continued to grow in major producing countries such as France and Italy as

surviving producers have intensified their production practices. Production has also grown in countries like Turkey, Iran, India and Pakistan, where irrigation water is available and higher-value fruit crops have replaced less profitable field crops.

Apple production in China had been growing steadily since the Second World War and was about equal to that of the USA in 1990. However, no one predicted that the rate of growth would be maintained from the higher base in 1990 so that China's production would exceed 20 million t by the end of the decade. Over the same period, production of apples in the rest of the world changed little (Fig. 2.2). Food and Agriculture Organization (FAO) data indicate that China's share of world apple production has gone from 10.7% in 1990 to 36.7% in the year 2000.

Many factors contributed to this growth. There was a pent-up demand for fresh fruit among the huge (1.2 billion) Chinese population. Demand for apples was very responsive to various indicators of economic growth (Han *et al.*, 1999). Fruit supplies had been limited in order to provide security of grain supplies. Beginning in 1978, with the introduction of the 'production responsibility' system for agriculture, the Chinese government gradually relaxed the restrictions on what peasant farmers could grow, how they could market their product and what price

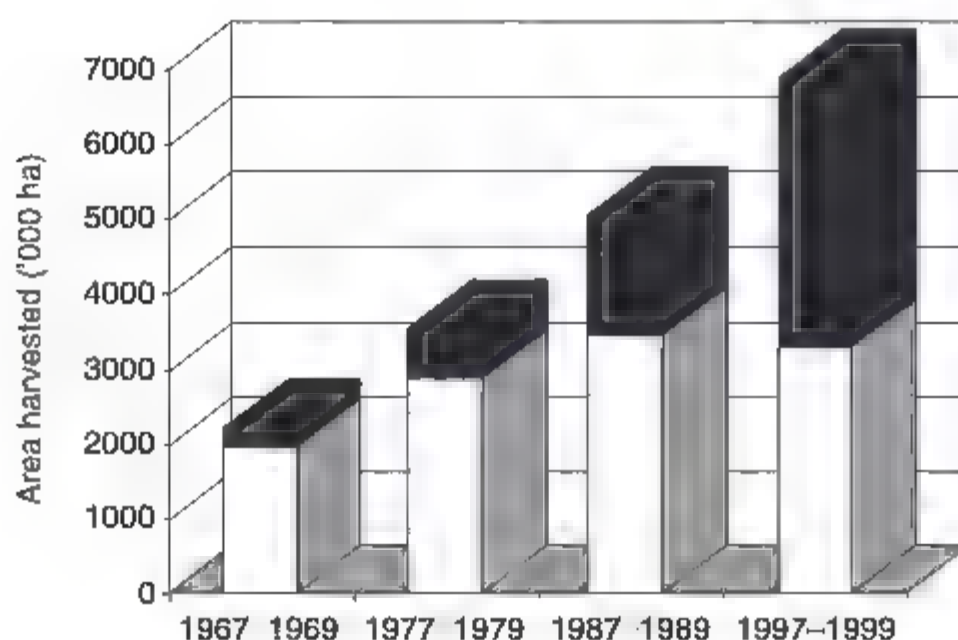


Fig. 2.1. Apple area harvested in China ■, rest of the world □ and total world. 1967–1999 (from FAO, 2000)

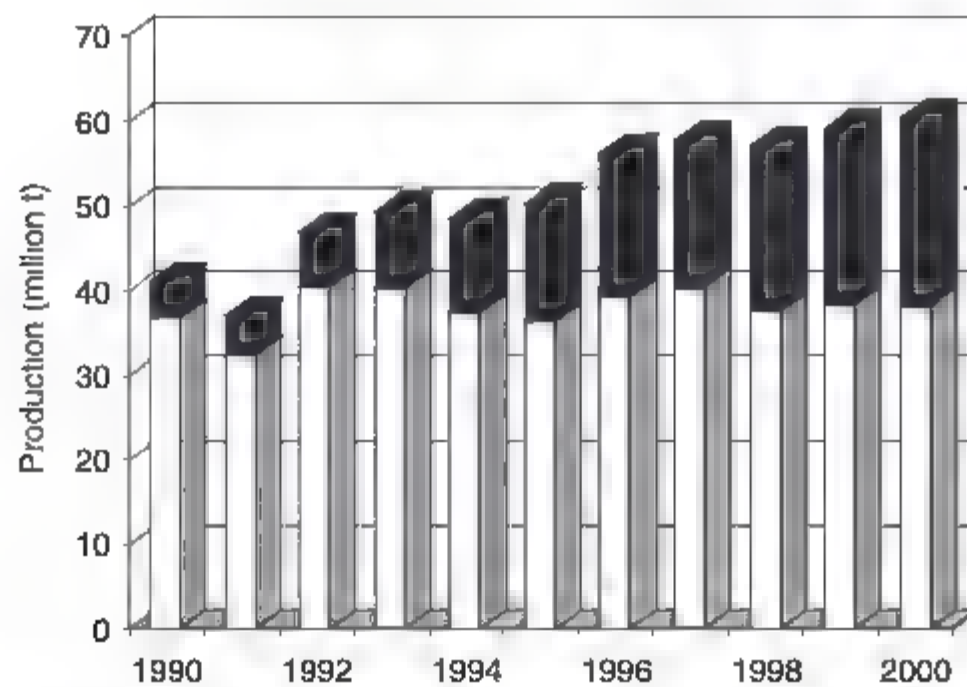


Fig. 2.2. Apple production harvested in China ■, rest of the world □ and total world, 1990–2000 (from FAO, 2000)

they could receive. A smallholding that would provide a meagre living from rice sold at low government-ordained prices could generate a many times greater income from fruit sold at market prices. In addition, the leaders of communes and townships encouraged fruit production and processing as a way to boost rural incomes.

Most of China's apple production occurs in six provinces: Shandong, Shaanxi, Henan, Hebei, Liaoning and Shanxi, with about half occurring in Shandong and Shaanxi alone (China State Statistic Bureau, 1999). Technically, ownership of the land is distributed in small lots (less than 0.1 ha) to individual peasants. However, titles are frequently unclear. Through assorted institutional arrangements, some large contiguous blocks are under common leadership or management. No precise evaluation of the calibre of production practices employed has been reported, but these appear to vary widely. Sophisticated practices appear to be most widespread in the coastal province of Shandong. United States Department of Agriculture (USDA) data indicate that 'Fuji' in 1999 accounted for 45% of acreage and production and 'New Red Star' for 12%. Cultivars developed in China, such as 'Chalajin', 'Guoguan', 'Qinguan' and 'Jinguan', each accounted for less than 10%. 'Gala' was the western variety most popular for new plantings (Rutledge, 2000).

2.3 Commercial Practices

While many small or part-time operators in many countries continue to produce apples in traditional ways, the majority of commercial growers are increasingly exposed to best commercial practices from around the world. Greater ease of international communications, individual and group study tours, geographical diversification by multinational corporations, international alliances among growers, packers, nurseries, chemical companies, research and extension workers and so on, together with international coverage in most major fruit journals, have all played a part in increasing the homogeneity of commercial practices among the better growers.

Importers, wholesalers and retailers that buy fruit across international borders are increasingly concerned about how that fruit is produced and handled on its way to market. Standards for integrated production, such as the International Standards Organization (ISO) 9000 and Hazard Analysis and Critical Control Point (HACCP) protocols, are being demanded by more buyers and more government monitoring agencies. All these are shining a spotlight on current commercial practices and forcing the apple industry to move to generally accepted best commercial practices that improve the sustainability of production methods and reduce dependence on the use of chemical pesticides.

2.4 Cultivars

International information flow has also had a profound effect on the popularity of different apple cultivars. In most countries, growers continue to produce many cultivars that have been traditional in their region. However, newer cultivars have gradually been introduced for varied production and marketing reasons. For example, 'Red Delicious' and 'Golden Delicious' became popular in the USA in the 1950s and 1960s, partly because they provided attractive display opportunities for the booming supermarket retail business. 'Granny Smith' entered the market initially as an off-season cultivar. Production expanded in the northern hemisphere in the 1970s and 1980s as the demand grew for a tarter apple. The arrival of 'Jonagold', 'Gala', 'Fuji' and 'Braeburn' in the 1980s and 1990s coincided with the growth of hypermarkets and a large expansion of the retail shelf space devoted to produce.

Since per capita consumption of apples in most developed countries is flat, in general new cultivars can only expand their share of

the apple business at the expense of existing cultivars. The battle between cultivars is being fought in the nurseries, in the orchards, in the packing and storage facilities and on the retail shelf. The shake-out among cultivars can be expected to continue. Some of the older, local cultivars are rapidly disappearing, while others have proved more resilient. In turn, some of the newer cultivars have flourished in certain districts while some have not.

Official data on cultivars are either very limited or not available at all for many countries. Estimates of cultivar trends for 34 major producing countries (not including China) were developed by O'Rourke (2001). These suggest that the volume of production of 'Red Delicious', 'Golden Delicious' and 'Granny Smith' apples will be stable in the next few years, but that there will be significant gains in volume of 'Gala', 'Braeburn', 'Pink Lady®' and, to a lesser extent, 'Fuji' (Table 2.1). If China is included, 'Fuji' production will continue to leap ahead because China is estimated to have 45% of its production in this one cultivar.

Table 2.1. Major producing countries excluding China, cultivar trends ('000 t) (from O'Rourke, 2001)

Cultivars	2000 Estimated	2005 Projected	2010 Projected
'Red Delicious'	5,334	5,422	5,423
'Golden Delicious'	4,982	5,222	5,212
'Granny Smith'	1,719	1,805	1,828
'Rome Beauty'	565	560	540
'Cox's Orange'	218	232	226
'McIntosh'	543	655	665
'Jonathan'	678	737	727
'Idared'	805	1,087	1,148
'Fuji'	1,433	1,671	1,857
'Gala'/'Royal Gala'	1,688	2,188	2,594
'Braeburn'	429	574	710
'Elstar'	413	494	535
'Gloster'	210	221	214
'Jonagold'	1,039	1,168	1,208
'Jonagored'	199	240	285
'Pink Lady®'	61	129	194
All other	5,997	6,726	7,063
Grand total	26,313	29,131	30,429

The outcome of these changes in cultivars is that all the major exporting countries can offer plentiful supplies of both traditional and newer cultivars. Thus, year-round competition in almost every cultivar is likely to intensify.

2.5 Controlled-atmosphere Storage

Controlled-atmosphere (CA) storage was originally adopted as a tool to permit companies to market selected cultivars of apples for an additional month or two. As the technology has evolved, CA has enabled more cultivars to be held for longer periods. It has been an excellent tool for managing the flow of product to market. However, the advantages of CA in lengthening the sales period have been offset by the increasing availability of new-crop apples from the opposite hemisphere within 6 months of harvest. In recent years, CA storage has been used increasingly to ensure better firmness or to control fruit disorders that affect apples in regular cold storage. CA has become a highly complex tool for ensuring that apples meet customer quality standards at any time during the marketing year. As CA has become more pervasive, buyers have been less willing to pay a premium for these quality improvements.

CA capacity continues to grow in Europe, North America and the southern hemisphere because larger operators want the flexibility in marketing that CA provides (USDA MNS). The volume of apples still in CA storage in the northern hemisphere during later months of the season continues to rise. This has tended to reduce the price advantage formerly earned by late-season CA fruit. That fruit is now beginning to crowd the market and depress the price of new, off-season apples from the southern hemisphere. Essentially, the seasonal niches that CA storage once made possible have shrunk.

2.6 Market Uses of Apples

The primary market for most apples produced around the world is for domestic fresh use. Where processing facilities are not avail-

able, apples that are not marketable as fresh are used for animal feed or are wasted. In a few countries, such as the USA, Germany and Australia, there has been a large market for apples processed into forms such as slices, pie fillings, dried apples, apple sauce, juice or cider. Specific cultivars were, and continue to be, grown because of their suitability for these processed products.

The development in the 1960s of an effective technique for concentrating apple juice to a six-to-one ratio has revolutionized the global market for apple juice. Because of its bulk and low value, single-strength apple juice had to be marketed near the point of production. Regional processors were effectively buffered from invasion by outside suppliers. However, a turnkey plant to process concentrated apple juice (CAJ) could be placed anywhere there was a large supply of cull apples. The resultant product could be shipped in bulk containers around the world at low cost. It could be stored without refrigeration and reconstituted on demand. Many CAJ plants (most focused primarily on exports) were erected in major apple-producing countries, such as Argentina, Chile and Poland. Global supplies of CAJ rose rapidly in the 1970s and 1980s (Table 2.2). Growth has slowed in the 1990s as the apple industry in total has shrunk in eastern Europe and the former Soviet Union.

This world pool of CAJ enabled beverage companies and dairies that had formerly lacked access to regional supplies of raw processing apples to build new beverage lines based on the imported CAJ. They competed directly with the traditional apple processors that had previously controlled locally available raw materials. They provided added competition in the market for apple-juice products, but created little new demand for domestically produced CAJ because they could get their supplies more cheaply from the world market. Juice became the primary use for processed apples, and the world CAJ price became an important influence on the price of apples for other processing uses (Baumes and Conway, 1985).

The percentage of apples processed in each country is not known precisely. However, from the USDA Global Agriculture

Table 2.2. Concentrated-apple juice production and ending stocks, selected countries, 1992–2000 (t)
(from USDA FAS)

Country/region	1993/94	1994/95	1995/96	1996/97	1997/98	1998/99	1999/2000p
Production							
Germany	60,686	74,571	69,901	68,630	73,903	67,025	70,000
Austria	23,450	14,300	11,500	25,000	30,000	24,700	25,000
Argentina	62,800	65,350	64,400	86,737	59,493	84,800	51,600
USA	146,612	166,547	156,150	134,310	131,966	145,285	150,000
Poland	135,000	108,000	88,000	136,413	145,000	130,000	110,000
N hemisphere	509,306	509,999	454,797	451,090	519,852	515,128	500,500
S hemisphere	145,054	141,805	157,040	189,414	152,243	163,274	132,162
World total	654,360	651,804	611,837	640,504	672,095	678,402	632,662
Ending stocks							
Germany	164,056	181,286	91,347	81,021	115,000	100,114	87,575
Austria	27,900	25,600	15,900	9,200	13,500	11,200	8,400
Argentina	135	385	0	6,948	0	0	0
USA	0	0	0	0	0	0	0
N. hemisphere	200,531	208,446	107,457	90,241	132,520	129,834	97,495
S hemisphere	675	885	500	7,348	8,165	3,095	1,595
World total	201,206	209,331	107,957	97,589	140,685	132,929	99,090

p, preliminary.

Information Network (GAIN) data on major producing countries, we can estimate what the general level is by region. In 1998/99, it ranged from 6% of all apple production being processed in China to 35% in North America and the southern hemisphere and to over two-thirds in eastern Europe. In North America, about half of all processed apples were converted into apple juice. In countries such as China and those in eastern Europe or the southern hemisphere, most processed apples were converted into CAJ and most of that CAJ was then exported.

A final major use for apples is for export fresh. The percentage of world apple production entering international trade in fresh form has been between 8 and 10% for many years (FAO, b). This has occurred because many of the best target markets for exports, such as the USA and the European Union, have also had an increase in their own apple production. However, exports have also become critical to the economic vitality of the apple industry in many countries and growing districts.

For example, Chile and New Zealand have small domestic markets and must find fresh export outlets for more than half of their total apple production. In countries such as the USA, France, Italy and South Africa, the domestic market is large but not growing fast enough to absorb the increased supplies at a profit. Certain growing districts, such as Washington State in the USA or the Alto Adige in Italy, whose productive capacity far exceeds what the domestic market can absorb, must also export fresh apples to remain financially viable.

2.7 The Conundrum of Export Markets

One-fifth of the world's population lives in developed countries where incomes are high and stable but demand for fresh apples and for apple products is flat. The remaining four-fifths of the world's population lives in developing countries, where incomes are relatively low and unstable, although generally rising. When incomes in the developing

world rise, so does the demand for apples. The conundrum for apple marketers is that stable markets for fresh apple exports are not growing and growth markets are not stable. For example, economic setbacks in Mexico in 1994, in Asia in 1997 and in Russia and Latin America in 1998 reduced apple exports to these countries dramatically while the crises lasted.

Eight of the top ten apple-importing countries in 1998 were developed countries (Table 2.3). The exceptions were Russia and Brazil, both of which suffered severe import declines in subsequent years. In contrast, four of the top ten major apple-exporting countries in 1998 were developing countries: Chile, South Africa, Argentina and Iran. The wide differences in costs and sources ensures that global trade channels are supplied with a wide range of qualities and prices of fresh apples.

2.8 Export Economics

The economics of product exporting is relatively simple in theory. If an exporter can deliver goods to a receiving country at a cost (including shipping, handling and other fees) that is below the price in the importing

country, trade will take place. However, importing firms may prefer to buy imported rather than domestic products for other reasons, such as timeliness, availability, variety, quality, attractive promotion, as an alternative source of supply, because of personal or business links or for many other less easily quantified reasons. In turn, importing firms may prefer a higher-priced domestic product for similar reasons. Exporting firms may also be willing to make uneconomic sales in order to maintain the loyalty of customers.

In produce, the 'new crop' designation has always had special appeal. Traders believe that new arrivals stimulate fresh interest among otherwise jaded consumers. Hence, the continuing interest in new-crop apples from the southern hemisphere. Other factors affect the willingness of exporters to participate in trade. Governments may provide direct export subsidies, as in the case of the European Union. They may provide indirect subsidies, as the USA does through promotional subsidies (the Market Access Program) or through tax relief for exports (OECD Committee for Agriculture, 1991). Governments also frequently encourage exports in subtle ways because they need to earn scarce foreign exchange that can be used to purchase strategic imports.

Table 2.3. Top ten fresh-apple importers and exporters, 1998 (by volume and value) (from O'Rourke, 2000)

Rank	Country	Exporters		Importers	
		Volume (t)	Value (US\$ '000)	Country	Value (US\$ '000)
1	France	766,207	488,559	Germany	438,656
2	USA	582,234	350,454	UK	390,920
3	Chile	575,601	233,443	Russian Fed	137,892
4	Italy	540,138	258,773	Belg-Lux	204,954
5	The Netherlands	338,901	186,582	The Netherlands	163,745
6	Belg-Lux	335,470	238,857	China ^a	113,032
7	New Zealand	291,720	204,083	USA	95,390
8	South Africa	242,000	124,470	Spain	79,463
9	Argentina	227,520	118,093	Brazil	55,433
10	Iran	190,000	30,000	Canada	84,749
	Top ten	4,089,791	2,233,314	Top ten	1,764,234
	Total world	5,176,391	2,660,958	Total world	2,807,216
	Top ten %	79.0	83.9	Top ten %	62.8

^aIncludes the province of Taiwan.

Belg-Lux, Belgium and Luxemburg

Another major influence on trade is fluctuation in relative exchange rates. Such fluctuations change the price signals that buyers and sellers receive from the market. For example, in 1990, one US dollar equalled 2.6 South African rands and 337 Chilean pesos. By the end of the 2000 marketing season, one US dollar equalled approximately 7 rands and 560 pesos. If a US importer paid US\$10 per box for apples in both 1990 and 2000, the South African exporter would have received almost three times as many rands in 2000 as in 1990 but the Chilean exporter only 66% more pesos. The US importer would have received a signal that market demand was flat, the Chilean exporter a signal that demand was growing modestly and the South African exporter a signal that demand was soaring.

A stronger currency gives an importing country an advantage in bidding for products on the world market. Conversely, a weaker currency gives an exporting country a short-term advantage in undercutting competing suppliers. The advantage is usually short-term because domestic inflation rapidly offsets any nominal increase in import price. In contrast, a stronger currency makes life difficult for exporting firms in that country, while a weaker currency penalizes importing firms. Market signals that are distorted by currency fluctuations are particularly troublesome in perennial crops such as apples. While producers can respond rapidly to an apparent increase in price by increasing plantings, the additional production generated may overhang the market for many years thereafter. Some of the recent increase in world apple production has resulted from such distorted price signals.

2.9 International Trade Laws and Trade Barriers

In most countries, putting foreign suppliers at an economic disadvantage relative to domestic suppliers is seen both as fair and as good politics. Thus, governments are willing to use trade barriers to help domestic producers. However, experience over two centuries has shown that such policies cause

consumers to lose, producers to become less efficient and trading partners to retaliate in a destructive spiral. The General Agreement on Tariffs and Trade (GATT) was set up in 1947 by a small core of developed countries. They had suffered a particularly severe bout of such 'beggar-my-neighbour' policies in response to the Great Depression. GATT sought to develop rules governing international trade and to gradually phase out protectionist devices. In a series of negotiating rounds over the next five decades, GATT was successful in reducing many trade barriers and in recruiting most market economies as members. At the core of GATT's success was the most favoured nation (MFN) principle. Members agreed to grant all other members the same trade concessions (in terms of access, quotas, tariffs, etc.) as they granted to their most favoured trading partner.

GATT, however, made little progress in liberalizing trade in agricultural products until the Uruguay Round was completed in 1994 and, even then, made only a modest start. The agency into which the GATT was converted, the World Trade Organization (WTO), has failed so far to build on the small gains of the Uruguay Round. One critical exemption to MFN that was allowed by GATT has had a lasting impact on the liberalization process in agricultural products. GATT allowed member countries to form regional free-trade agreements, which could liberalize more rapidly than the general GATT level. However, just two of those free-trade areas, the European Union and the North American Free Trade Agreement (NAFTA), now account for half of world trade. The European Union, in particular, has used its strong influence within GATT WTO to protect its internal agricultural market by impeding global trade liberalization. It has aggressively pursued many new bilateral trade links with third countries because these enable it to exempt sensitive agricultural products. The European Union has found powerful allies in countries like Japan, South Korea, Taiwan and even China, which fear that their agricultural industries could not withstand global competition.

Modest liberalization in agricultural trade has accompanied the implementation

of the Uruguay Round of GATT and of the various regional free-trade agreements. The European Union has lowered its tariff barriers for non-member countries but has left its variable levies intact. Other countries have reduced their tariffs on agricultural products as part of their GATT WTO commitments. Regional free-trade areas, such as NAFTA and Mercosur (which includes Argentina, Brazil, Paraguay and Uruguay), have reduced barriers to member countries. For example, Mexico's duties and tariff-rate quotas on fresh apples from its NAFTA partners, the USA and Canada, will be phased out by 2004. However, countries that are not members of NAFTA will find themselves at an increasing disadvantage in selling to the Mexican market. Many countries have moved to resolve this problem by negotiating bilateral agreements with Mexico. Other regional free-trade agreements, such as Mercosur, will also put non-members at an increasing disadvantage. Even bilateral agreements discriminate against those countries that are not included. The longer a comprehensive global solution to agricultural liberalization is delayed, the more difficult it will be to unravel these growing trade distortions.

2.10 Global Apple Consumption and Demand

We distinguish here between apple consumption and apple demand because they have quite different implications for the global apple industry. Consumption is a static, one-dimensional measure of the volume of apples consumed in any time period. Per capita consumption is an average figure derived when the total volume consumed is divided by the total population. Per capita consumption data are useful indicators for comparing the popularity of apples relative to other fruits, in different time periods or in different countries.

However, measuring consumption of a minor food product like apples is difficult and tends to have a low priority with most government statistical agencies. Thus, official series of per capita consumption data are not

available for most countries. The USDA and the FAO both use a balance-sheet approach to estimate consumption indirectly. Total supplies are considered to equal beginning inventory plus production plus imports in the period. Fresh consumption is assumed to be the balance of those supplies remaining after exports, processing use, withdrawals, waste and losses and closing inventory are subtracted. For most fresh products, beginning and ending inventory are assumed to be zero, that is, there is no carry-over from one year to the next. Since consumption is measured as a residual, any errors in measurement in any of the other variables affects the estimate of consumption.

FAO data report per capita consumption of all apples, but do not separate fresh from processed. From USDA GAIN reports, we estimated per capita apple-consumption trends between 1990 and 1999 for 32 apple-producing countries (Table 2.4). For 20 of the 32 countries, the trend was downwards. The major increases were in China (up 400%), Brazil (up 40%), Taiwan (up over 70%) and Turkey (up about 20%). All but Taiwan were low-income, developing countries. We estimated comparable data for 22 countries that import almost all of their apple supplies (Table 2.5). In general, they showed a positive trend for the period 1990–1996. Thereafter, most suffered consumption declines related to the widespread economic setbacks of the late 1990s.

Demand is a broader concept than consumption. It describes the relationship between the quantity consumed and the price paid. Demand is also a much more difficult concept to measure because it requires accurate data series on consumption, prices, income, tastes and preferences and other factors that might shift demand. Clearly, it would be more beneficial to the apple industry if the average US consumer were willing to buy 40 lb. of fresh apples annually at US\$1 per lb. rather than the 20 lb. of fresh apples actually consumed. However, in a normal demand relationship (what economists call the demand curve), consumers will only be willing to consume more if the price is lower. One indicator of the strength of demand is what percentage decrease in price would be

Table 2.4. Apple-producing countries: estimated per capita consumption, 1990–1999 (kg per capita) (from O'Rourke, 2000).

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999p
Austria	35.89	30.97	29.15	36.85	32.38	34.14	23.30	25.00	23.73	21.30
Belgium	23.68	20.33	25.36	25.56	29.51	27.69	23.10	21.10	19.63	20.46
Denmark	17.90	14.75	16.34	15.42	16.33	16.51	17.76	20.89	20.82	21.41
France	17.99	13.61	13.80	14.54	16.47	15.69	16.77	15.26	15.61	15.93
Germany	25.01	18.80	32.45	20.05	22.84	18.93	21.06	17.54	21.03	19.99
Greece	16.90	16.22	21.52	21.30	21.40	21.90	18.60	22.08	23.99	24.87
Italy	22.71	20.26	23.46	19.87	21.48	18.78	21.88	21.77	24.23	25.43
Netherlands	23.09	12.00	34.43	23.88	27.26	24.67	24.10	21.26	19.06	19.04
Spain	17.56	14.76	19.54	18.69	17.42	17.64	17.00	17.01	16.85	16.94
Sweden	18.25	15.53	16.78	16.13	17.20	16.37	15.63	17.61	16.40	16.97
UK	12.18	10.89	11.61	11.19	10.73	9.74	9.73	8.86	10.02	10.04
EU-11	20.12	16.22	21.87	18.07	19.28	17.55	18.15	16.97	18.27	18.31
Norway	15.70	12.80	16.67	16.62	15.59	15.54	14.86	13.87	14.40	14.34
Bulgaria	11.80	8.02	6.70	6.50	5.29	5.95	9.05	9.52	7.62	9.05
Hungary	26.58	24.17	20.36	28.99	15.82	12.81	16.16	16.20	15.93	15.77
Poland	n/a	n/a	12.85	14.57	9.20	8.84	17.66	13.75	8.55	11.59
Romania	n/a	n/a	18.30	37.00	17.50	16.40	15.45	18.01	13.61	16.37
Slovakia	n/a	n/a	n/a	12.22	10.09	6.05	12.79	12.97	13.87	14.77
Yugoslavia	n/a	11.05	22.01	14.61	10.50	9.50	12.81	11.40	8.99	8.95
Other Europe	n/a	n/a	n/a	20.65	11.92	10.85	15.34	14.32	10.95	12.89
Argentina	7.12	7.28	7.74	9.26	8.22	12.40	11.58	9.09	10.02	9.51
Australia	9.39	9.96	10.25	8.94	9.50	8.25	9.29	8.38	8.44	8.89
Brazil	2.90	2.37	3.03	3.16	4.26	4.35	4.15	4.14	3.91	4.11
Chile	6.83	5.23	6.25	6.52	6.57	6.47	6.44	6.14	6.59	6.49
New Zealand	16.14	13.67	15.12	15.31	15.23	14.44	14.57	14.43	30.59	17.32
South Africa	4.94	4.49	5.33	5.55	5.11	5.94	5.75	5.07	4.64	4.85
S hemisphere	4.56	4.13	4.78	5.01	5.50	6.14	5.93	5.44	5.59	5.52
China	n/a	3.73	5.26	7.23	8.80	10.91	13.13	13.14	14.62	16.05
Japan	6.52	3.54	6.61	6.62	6.51	6.38	6.05	6.04	5.59	5.99
Taiwan	4.37	5.54	6.14	5.52	6.64	5.63	6.52	6.76	7.49	7.48
Turkey	30.81	29.98	33.66	33.33	32.18	31.62	32.76	37.78	35.87	36.48
Asia	2.29	5.02	6.82	8.38	9.29	10.98	12.85	13.50	14.67	15.96
Canada	11.64	10.87	13.02	12.20	12.22	12.52	11.95	11.58	12.01	11.76
Mexico	3.57	4.35	5.18	6.67	5.37	4.62	4.87	6.69	4.36	5.41
USA	9.00	8.32	8.79	8.74	8.91	8.57	8.77	8.40	8.72	8.83
N America	7.96	7.60	8.27	8.51	8.33	8.34	8.08	8.23	7.91	8.21
Russia	n/a	n/a	n/a	4.86	5.03	4.79	5.72	5.27	4.37	4.11
All 32 countries	n/a	n/a	n/a	9.61	9.95	11.37	11.91	11.95	12.53	13.29

n/a, not available; p, preliminary; EU, European Union

Table 2.5. Per capita disappearance of fresh apples, selected importing countries, 1990 and 1994–1998 (kg per capita) (from O'Rourke, 2000)

Country and region	1990	1994	1995	1996	1997	1998
East Asia						
Singapore ^a	9.65	12.12	12.36	10.00	10.48	9.39
Hong Kong ^a	9.84	11.85	11.35	9.20	8.59	8.62
Taiwan	3.82	5.85	5.18	6.14	5.46	6.80
Malaysia	1.28	2.45	2.71	2.57	3.09	2.02
Thailand	0.42	0.98	1.09	1.08	0.63	0.61
Indonesia	0.01	0.17	0.23	0.19	0.36	0.10
Subtotal	0.71	1.21	1.26	1.21	1.22	1.08
Middle East						
United Arab Emirates ^a	13.32	20.40	24.39	38.88	18.20	16.47
Bahrain	8.11	14.15	13.86	13.53	11.93	10.17
Oman	4.41	5.33	3.50	1.35	2.19	2.30
Kuwait	5.20	12.75	12.48	14.04	13.75	11.13
Saudi Arabia	8.27	6.89	6.85	7.00	6.76	5.60
Libya	4.02	2.49	1.48	3.75	1.73	2.06
Egypt	0.00	0.35	0.33	0.31	0.45	0.59
Subtotal	2.52	2.87	2.84	3.11	2.55	2.43
Latin America						
Panama	1.93	2.12	2.09	2.12	2.06	2.27
Costa Rica	1.60	2.06	2.04	1.92	1.99	2.46
Colombia	0.75	1.30	1.48	1.43	1.61	1.42
Venezuela	0.59	0.95	1.11	0.66	1.32	1.90
Peru	0.11	0.73	0.63	0.51	0.51	1.63
Dominican Republic	0.14	0.51	0.49	0.73	0.51	0.79
El Salvador	0.95	0.48	0.99	0.69	0.88	0.25
Honduras	0.42	0.25	0.32	0.38	0.67	0.17
Nicaragua	0.06	0.14	0.16	0.15	0.20	0.20
Subtotal	0.56	0.96	1.05	0.92	1.12	1.39

^aRe-exports subtracted from imports.

needed to achieve a given percentage increase in consumption. At the retail level, a 10% decline in the price of fresh apples would be needed to boost consumption by 10%. However, because marketing margins in food distribution are relatively fixed, a 20% or greater decline in grower price would be needed to boost consumption by 10%.

2.11 Consolidation in Food Distribution

Changes in the food-distribution system are changing the way in which consumer needs are being passed back to producers. The

most systematic approach to studying these changes has occurred at the Retail Food Industry Center at the University of Minnesota in St Paul, Minnesota (see, for example, Larson, 1997; Kinsey, 1998). Three related phenomena are driving these changes. First is the entry of non-traditional retailers, such as discount chains, hypermarkets, supercentres and warehouse club stores, into food retailing. While their appeal to consumers goes beyond price factors, these formats have used economies of scale in purchasing and internal management efficiencies to sell comparable food products at prices below those of conventional super-

markets. Many have introduced their new concepts internationally. Traditional super-market chains have scrambled to regain their competitive edge by getting bigger through mergers and acquisitions and by seeking similar purchasing and logistical efficiencies. Many of them, too, have gone international. As a result, increasing concentration, intense competition among retail formats and downward pressure on supplier prices have become the norm all over the world. In the case of apple pricing, as retailers have got bigger they appear to have acquired some market power (P.M. Patterson, 2000, unpublished data)

In most countries, four retailing organizations now account for 50% or more of all food sales. Consolidation has led to ever fewer and larger buyers. Most larger buyers want to deal with fewer, larger suppliers that can meet their product needs for 12 months of the year, can invest in sophisticated information systems and can provide the many warranties and services that retailers and their customers now demand. This has resulted in a frantic scramble among suppliers to position themselves to capture some of the business of the larger retailers. Consolidation is now taking place at every level of the supply system, including packers, shippers, marketers, brokers, exporters and importers. In their drive to become larger and more efficient, the surviving suppliers are becoming less tolerant of individual growers or growing districts that cannot meet ever-higher retailer standards. There is no sign that these forces for change in the food-distribution system will abate any time soon.

2.12 Stimulating Apple Demand

While efforts to increase per capita consumption of fresh apples may seem desirable, they may be counter-productive if they can only be secured by sharp reductions in grower price and a decline in grower revenues. What is needed is a positive shift in the whole demand curve, either persuading consumers to purchase the same quantity but at a higher price, or a greater quantity at the same price, or some combination of the two.

The most obvious demand shifter is growth in per capita income. However, in developed countries, where per capita income and per capita consumption of fresh apples are already high, income increases have little positive effect on per capita consumption. In contrast, in developing countries, where per capita income is low, increases in income do lead to substantial increases in per capita consumption of items like fresh apples.

These findings suggest that the major apple-exporting countries would get greater returns by targeting more of their sales efforts and promotional dollars in developing-country markets. In developed-country markets, where the income effect is weak, sales and promotional efforts need to be targeted at changing consumers' tastes and preferences for apples. Many in the industry believe that health claims can be exploited to achieve this. However, many other fruits and vegetables can make comparable health claims. In addition, enjoyment is a key reason for consuming any food. There is a danger that too heavy an emphasis on the health aspect could create a negative image in the minds of many consumers. Work by Baker (1999), suggests that, because consumers vary in the depth of their concern for food safety and health, such promotions would have to be targeted more precisely than they have been in the past. While the appropriate promotional themes and strategies remain to be determined, there is no doubt that a major commitment of funds would be needed to change consumers' attitudes and purchasing behaviour substantially.

A number of leaders in the global apple industry have become convinced that they can gain a competitive advantage for their company by segmenting their marketing effort by cultivar. They are forming so-called 'marketing clubs', in which selected growers, marketers and nurseries form an international alliance to manage the licensing, production and marketing of a specific cultivar throughout the world. The prototype effort is the International Pink Lady® Alliance, which charges participants membership, management and promotional fees and regulates quality, packaging and other common standards. The sponsors hope that this effort will

boost demand for the 'Pink Lady®' cultivar to the extent that the added revenue generated will more than compensate for the added cost of belonging to the alliance. Clubs for other cultivars are being formed.

A number of questions have still to be answered regarding these clubs. Can they generate sufficient added revenue to offset the added costs? Even if there is a profitable market segment for 'Pink Lady®', how many market segments for other varieties can be exploited profitably? Even if these market segments can be exploited successfully, will it be at the expense of other cultivars, so that total apple demand is not improved? Will promotions for individual cultivars be most effective as a complement to or as a replacement for current generic apple-advertising programmes? Research is needed into these questions before industry groups invest too heavily in the marketing-club approach.

2.13 Need to Balance Supply and Demand

Individual markets are like pools of sea water on a rocky beach. At low tide, they can be isolated and function independently. But an errant wave can at any time rush in and sweep over a number of nearby pools and, at high tide, all pools may be submerged and connected. Markets experience the same sort of ebb and flow. Local markets can have temporary gluts or shortages that only affect local prices. However, if those gluts or shortages persist, product will flow from other areas of surplus to areas of shortage. Modern storage, transportation and communication technology has enabled apple suppliers in any part of the world to respond rapidly to any temporary imbalances elsewhere.

The reality of globalization of markets is that most local markets are connected with the global market most of the time. Thus, the global balance of supply and demand has become a powerful influence in all but the most isolated local markets. Increasingly, since 1990, there has been an excess of global supply over global demand that has depressed prices. The reasons for this imbalance have already been explained. Supply

has increased in response to past favourable prices, government supports and exchange-rate illusions. That supply will continue to increase as more trees reach full bearing unless specific actions are taken to remove areas from production. Demand, on the other hand, has been static in the developed world and has been halted, at least temporarily, in the developing world by economic setbacks and by the failure of agricultural trade liberalization.

2.14 Future Outlook

The consolidation of the apple industry into larger, more viable units at the growing, packing, storage and marketing levels is likely to continue. Less and less of the apple volume will be in the hands of marginal growers, marginal producing districts and marginal producing countries. The surviving producers will employ every available technology to increase yields per hectare and reduce unit costs. Experimentation with new cultivars and new marketing models will continue.

However, the biggest single influence on the global apple industry in the next decade will be what happens to the 2.3 million ha of apple orchards in China. Because many of its trees are not yet at full bearing, China's average yield per hectare in the year 2000 was still below 10 t. With normal maturation of orchards, average yields can be expected to increase by at least 50% in the next decade. Thus, by 2010, Chinese apple production could exceed 35 million t. This would increase global supplies by an average of 1.3 million t (about 2.0%) each year for the next decade. In the same period, global supplies of many other fruits are also expected to increase.

If, as expected, China is accepted as a member of the WTO, it will become tied more closely to the world economy and will be less free to pursue the 'China first' policies of the past. Thus, exports of Chinese fresh apples and of CAJ are likely to increase. This will heighten competition in apple markets around the world and will intensify pressure on other producers and producing districts to rationalize their operations in order to survive.

Clearly, too, any effort to control global apple supply or boost global apple demand will have to include China. If the rest of the world bears these costs, it will rapidly become clear to them that China is getting some of the benefits of improved prices without paying any of the costs (the 'free rider' problem). However, China does not yet have the organizational structure capable of working with the promotional agencies of other major exporting countries.

2.15 Concluding Comments

The global apple industry is entering uncharted waters. It needs new maps, new vessels and a new sailing plan to effectively navigate those waters. It needs general acceptance of the present realities, a vision of how to move forward and a willingness to take bold actions to put that vision into effect. A number of global institutions have sought to build such a vision and plan of

action. The Southern Hemisphere Association of Fresh Fruit Exporters (SHAFFE), at its October 1999 meeting in Atlanta, set up a task force to study future joint actions (Dall, 1999). In October 2000, a broader organization consisting of representatives from leading European and southern hemisphere apple producers set up the World Apple and Pear Association (WAPA) to tackle the same issues that had become even more pressing in the previous year (Anon., 2000). WAPA hopes to attract participation from the USA, China and other leading producing countries.

The producing districts, industry organizations and firms that survive in the 21st century will be those that best understand the changing environment in which they must both compete and cooperate. They will be those that continuously strive to lower unit costs, produce higher-quality products and provide the distribution system and consumers with continually improving customer service.

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3 Genetic Improvement of Apple: Breeding, Markers, Mapping and Biotechnology

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3.1 Traditional Breeding

The genetic improvement of scion cultivars is the primary focus of this chapter, but the approaches used are also relevant to rootstock and ornamental *Malus* breeding. Rather than emphasizing breeding methodology, an overview of the current status of scion breeding will be detailed (Plate 3.1). The review of apple breeding by Janick *et al.* (1996) provides information on apple origin and early development, *Malus* species, modern breeding objectives, breeding techniques, resistance breeding and biotechnology. Information on apple breeding is also

reviewed in Brown (1975). Chapters on specific areas of breeding, such as pollen collection or mutation breeding, are reviewed in Janick and Moore (1983).

Apple has several constraints to rapid genetic improvement: a long juvenile period, large tree size, self-incompatibility and inbreeding depression. The last two characteristics mean that apple breeders cannot use standard backcrossing to incorporate a major gene from another cultivar or *Malus* species and still maintain cultivar identity. A modified backcross is used instead, with a different recurrent parent required in each generation of backcrossing.

Self-incompatibility enforces outbreeding and results in heterozygosity (Plate 3.2). While some inbreeding for genetic studies has been successful (Karnatz, 1994), inbred lines cannot be produced easily. Haploid lines are being developed by microspore culture, anther culture and parthenogenesis *in situ* (Lespinasse *et al.*, 1999; Keulemans and De Witte, 2000). These haploids are being doubled to obtain homozygous lines for genetic studies.

In the past, most important commercial cultivars arose as chance seedlings, and such seedlings continue to be commercialized today – for example, ‘Ginger Gold’ and ‘Cameo’. However, increasingly, popular new cultivars, such as ‘Fuji’, ‘Gala’, ‘Jonagold’, ‘Elstar’ and ‘Honeycrisp’, are derived from breeding programmes. To study genetic diversity, Noiton and Alspach (1996) analysed pedigrees of 50 apple cultivars being used in breeding. ‘Cox’s Orange Pippin’, ‘Golden Delicious’, ‘Jonathan’ and ‘McIntosh’ were the most frequent progenitors. Few of the cultivars sampled were substantially inbred, but continued inbreeding was a concern. Breeders are currently working with reduced genetic diversity and must attempt to expand the genetic base.

While cultivated apples are functionally diploid ($2x = 34$), many successful cultivars are triploids ($3x = 51$). Triploids occur spontaneously from unreduced gametes in $2x$ -by- $2x$ crosses. Triploids have much larger fruit and are of value to the industry. Breeders have tried to increase the likelihood of triploids by crossing tetraploids with diploids, with varying degrees of success. Some combinations produce no triploids, while others may yield 50–80% triploids. Bartish *et al.* (1999) used the mutagen oryzalin to induce chromosome doubling in somatic tissues of ‘Florina’ and ‘Falstaff’ to produce tetraploid clones for use in breeding. The quality of some triploid cultivars has prompted their use as parents, with the understanding that many of the seedlings produced will be aneuploids. Triploid cultivars are best used as pollen parents because the $2x$ gametes will have a selective advantage over aneuploid or unbalanced gametes. Researchers in Japan, Russia and the Ukraine

are active in the development and use of triploids in breeding.

Interspecific hybridization has played a major role in genetic improvement (Korban, 1986) and continues to be important in cultivar development. Interspecific hybridization will be aided by molecular markers that allow us to follow introgression of genes from wild species and enable us to differentiate hybrid offspring in crosses where apomixis or parthenocarpy is possible

3.1.1 Germplasm

Way *et al.* (1990) provided information on apple germplasm issues, research, important diseases, pests and horticultural problems and listed major apple germplasm centres. The International Plant Genetic Resources Institute (IPGRI) has a working group on *Malus* and *Pyrus*, with reports available online, suggestions for minimum descriptor lists for *Malus* and links to other germplasm centres at <http://www.cgiar.org/>

The Plant Genetic Resources Unit in Geneva, New York, part of the US Department of Agriculture (USDA) Agricultural Research Service (ARS), maintains 3739 accessions of *Malus*. Information on accessions may be searched in the Germplasm Resources Information Network (GRIN). A core collection (208 clones) and 40% of the base collection have been characterized for 25 morphological descriptors. Information on the USDA *Malus* collection can be searched at <http://www.ars-grin.gov/npgs/> The collection and management of wild *Malus* germplasm from its centre of diversity has provided additional sources of genetic variation for use in breeding (Hokanson *et al.*, 1997).

3.2 Apple-breeding Programmes: Their Objectives and Introductions

There are a large number of public and private breeding programmes around the world. The Pacific Northwest Fruit Tester’s Association (PNWFTA) summarized 57 apple-breeding projects in 25 countries (Ballard, 1998). Laurens (1999) surveyed apple-breeding programmes

internationally and summarized the primary objectives for scion cultivar improvement. Forty-two breeders from 29 countries responded to the survey. The most common objective is to combine in new cultivars high fruit quality with disease and pest resistance. Scab (*Venturia inaequalis* (Cooke) Wint.) and powdery mildew (*Podosphaera leucotricha* (Ell. & Ev.) resistance is stressed. Programmes develop cultivars adapted to an area's extreme climatic conditions. Genetic improvement of plant form involves selection of tree habits that allow high productivity and regular bearing. Hybridizations involve important commercial cultivars, old local cultivars and wild *Malus* species.

3.2.1 USA

In 1983 there were 19 public apple-breeding and genetic programmes in the USA (Brooks and Vest, 1985). Today there are only two full-time programmes – one each in Washington State and New York. Five other programmes in the USA divide their efforts between apples and other crops.

3.2.1.1 Arkansas

Rom and Moore (1994) reviewed the programme at the University of Arkansas, where the development of cultivars to support and expand the southern fruit industry was an objective. 'Stellar' and 'Arkcharm' were two of the cultivars released. Hybridizations have stopped, but advanced material continues to be evaluated.

3.2.1.2 Minnesota

Fruit breeding started at the University of Minnesota in 1878. Objectives are to develop cold-hardy, high-quality, disease-resistant cultivars. Noteworthy introductions include 'Haralson' in 1923, 'Regent' in 1963, 'Sweet Sixteen' in 1979, 'HoneycrispTM' in 1991 and 'Zestar' in 1999. The occurrence of several episodes of low temperatures, from -30 to -38°C, in the winter of 1995/96 provided data on cold-hardiness in the USDA core germplasm collection (Luby *et al.*, 1999).

3.2.1.3 New York

Cornell University's apple-breeding programme at the New York State Agricultural Experiment Station in Geneva started in 1895 and has released 63 apple cultivars. 'Cortland', 'Macoun', 'Empire' and 'Jonagold' are among its best-known releases. The scab-resistant cultivar 'Liberty' was released in 1978 and 'Freedom' was released in 1983. Brown and Terry (1997) reviewed the objectives of this programme in relation to traditional breeding, molecular markers and biotechnology.

3.2.1.4 Ohio

Mitch Lynd, a commercial grower, received seedlings from germplasm collected in Kazakhstan and planted them on his farm in 1999. This interest in disease-resistant, late-blooming, hardy material led to the development of the Midwest Apple Improvement Association, a grower group dedicated to the development of suitable cultivars for the Midwest. Additional information is at <http://www.hort.purdue.edu/newcrop/maia/default/html>

3.2.1.5 Purdue, Rutgers, Illinois (PRI, cooperative)

The accomplishments of this cooperative programme were reviewed by Crosby *et al.* (1992). Recent scab-resistant releases include 'Goldrush' and 'Enterprise' in 1993, 'Pristine' in 1995 and 'Scarlet O'Hara' in 2000. Purdue University is no longer making apple crosses, but selections are still being tested (see <http://www.hort.purdue.edu/>). Research at the University of Illinois emphasizes the improvement of apple by biotechnology

3.2.1.6 New Jersey

Rutgers University has named nine apple cultivars, with 11 additional cultivars released as part of the PRI cooperative. Well-known releases include 'Jerseymac' in 1961, 'Mollies Delicious' in 1966, 'Vista Bella' in 1974, 'Summer Treat' in 1981 and 'Suncrisp' in 1992. Fruit-ripening variants and their

effect on ethylene production is an area of interest (Gussman *et al.*, 1993).

3.2.1.7 Washington

Washington State University started apple breeding in 1994, with the goal of developing cultivars adapted to the stressful hot, dry and sunny climate of central Washington (Barritt, 1999). Seedlings are budded on to M.9 and planted in an evaluation orchard 19 months later. Fruit evaluation began in 1999.

3.2.1.8 Private breeders

There are several private apple-breeding programmes in the USA. Two programmes are part of commercial nurseries in California: Zaiger's Genetics in Modesto and Burchell Nursery in Oakdale. There are several smaller programmes led by hobbyists or commercial growers.

3.2.2 Canada

3.2.2.1 British Columbia, Summerland

Apple breeding started in 1924. Cultivars released for commercial use include 'Spartan' in 1936, 'Summerred' in 1964, 'Shamrock' in 1986 and 'Sunrise' in 1991. In 1996, 'Creston' ('Golden Delicious' × an advanced selection), 'Chinook' ('Splendour' × 'Gala') and 'Silken' ('Honeygold' × 'Sunrise') were named (Hampson *et al.*, 2000b). Two columnar or reduced branching cultivars, 'Scarlett Sentinel' and 'Golden Sentinel', were released in 1997 for the home gardener. The Summerland programme emphasizes determining consumer preferences and sensory testing for quality evaluation (Cliff *et al.*, 1998; Hampson *et al.*, 2000a). Their website is <http://www.em.agr.ca/>

3.2.2.2 Quebec

This programme originated in Ottawa in the 1940s and was transferred to St-Jean-sur-Richelieu in 1971. Releases include 'Blair' and the scab-resistant cultivars 'Rouville' and 'Richelieu' in 1990, and

'Belmac' and 'Primevere' in 1996. A columnar cultivar, 'MacExcel', was released for the home market. In 1996, several partnerships with private industry were established to test selected advanced apple selections in commercial orchards in comparison with commercially grown cultivars for their potential in the fresh market, long-term storage and juice and cider production. A part of the programme is to select hardy disease- and insect-resistant cultivars for home gardeners. Several rootstocks, with a range from vigorous to extremely dwarf, are also under evaluation and might be released for grower testing. Winter-hardiness, pest and disease tolerance, dessert quality and long shelf-life remain breeding objectives. Additional information on the programme, selections and cultivars is at <http://www.pgris.com/>

3.2.2.3 Nova Scotia, Kentville

This programme is known for the scab-resistant cultivars 'Nova Easygro' released in 1971, 'Novamac' in 1978 and 'Novaspy' in 1986. Controlled hybridization has ended, but the remaining seedlings and selections are being evaluated for potential release. Deslauriers *et al.* (1999) used descriptive sensory analysis (DSA) to define ten visual properties, nine flavour attributes and nine texture characteristics in apple and these were used to evaluate selections for the fresh and processing markets

3.2.2.4 Manitoba, Morden

The Dominion Experiment Station in Morden has as an objective the development of new varieties of trees and shrubs and evaluation of material for adaptability and value to the Canadian landscape trade. This programme released the ornamental crab apples 'Almey', 'Sundog', 'Garry', 'Selkirk' and 'Kelsey', also known as the 'rosybloom' crab apples. Scion cultivars released include 'September Ruby', 'Fall Red' and 'Red Sparkle'. Material developed at Morden can be grown in almost any location in Canada, due to the hardiness emphasis of the programme

3.2.3 Australia

3.2.3.1 Western Australia

Cripps Pink ('Pink Lady®') and Cripps Red ('Sundowner™') were named in 1985 by the Western Australian programme (Cripps *et al.*, 1993). Both cultivars are hybrids of 'Golden Delicious' × 'Lady Williams', a long-storing cultivar believed to be a hybrid of 'Granny Smith' × 'Rokewood' (parentage unknown). This programme was broadened in 1985 and started producing 12,000 seedlings per year until 1993. There are many advanced selections. In 1998 the goal was to maintain 50,000 seedlings. Information on this national programme is at <http://www.agric.wa.gov.au/>. A focus group, comprised of market representatives from Asia, Europe and Australia, provides feedback on the market potential of advanced selections.

3.2.3.2 Queensland

Breeding at the Queensland Horticulture Institute in the Department of Primary Industries (DPI) at the Applethorpe Research Station in Stanthope was started in 1964 to breed high-quality early red apples. An emphasis on scab resistance was added in 1986. 'Applethorpe Earlidel' was released in 1988 and 'Applethorpe Summerdel' in 1989. The website is <http://www.dpi.qld.gov.au/>.

3.2.4 Belarus

Kozolovskaya *et al.* (2000) reviewed the 70-year history in apple breeding, with 29 cultivars released. Resistance breeding began in 1984 and has yielded 136 progenies and over 30,000 seedlings. Over 100 selections have been propagated and several elites may be released.

3.2.5 Belgium

3.2.5.1 Gembloux

The programme at the Department of Biological Control and Plant Genetic Resources started in 1988. Its goals are to

combine durable resistance to scab, powdery mildew and canker with fruit quality and a range of desirable horticultural characteristics (Lateur *et al.*, 1999, 2000).

3.2.5.2 Heverlee

At the Fruitteeltcentrum at Katholieke Universiteit Leuven there are programmes in classical breeding (started in 1989), transformation, haploid induction and molecular understanding and characterization of self-incompatibility. 'Merlijn', a hybrid of 'King Jonagold' × 'Liberty', was the first release. 'Merlijn' has low susceptibility to scab and mildew. More information on these diverse projects is at <http://www.agr.kuleuven.ac.be/>.

3.2.6 Brazil

Apple breeding at the Empresa de Paequisa Agropecuaria e Extensao Rural de Santa Catarina S.A. Experiment Station of Cacador in Santa Catarina started in 1972 with seeds imported from America. A low chilling requirement for local adaptation and disease resistance are goals. 'Princesa' and 'Primicia' (scab-resistant) were released in 1986, the low-chill, scab-resistant 'Fred Hough' was named in 1994 and 'Catarina', a hybrid of 'Fuji' × a scab-resistant selection, was named in 1996. 'Imperatriz' and 'Baronesa' were released in 1997. In 1997, two low-chill cultivars were released: 'Condessa', with more scab and mildew resistance than 'Princesa', and the scab-resistant 'Duquesa'. In 1999, three cultivars adapted to regions with 100–500 chilling units or less were released: 'Eva', 'Anabela' and 'Caricia'. These are also resistant to necrotic leaf blotch (*Glomerella* spp.) and 'Caricia' is scab-resistant.

3.2.7 Bulgaria

Apple breeding started in the 1970s at the Fruit Growing Institute in Plovdiv. Objectives include early- and late-ripening apples with disease resistance and a range of tree habits: standard, compact, columnar or weeping (Djouvinov, 1994).

3.2.8 China

Many of the provincial fruit-research institutes in China have their own apple-breeding programmes, resulting in over 180 new cultivars being released from 1950 to 1995. Of these, the majority resulted from controlled hybridizations, eight were from open pollination, two were induced mutations and 11 were sports. 'Ralls Janet' is popular in China and is in the pedigree of many releases.

3.2.8.1 Hebei Province

The Hebei Changli Fruit Research Institute released 'Yanshanhong', a hybrid of 'Ralls Janet' × 'Richared Delicious', in 1989.

3.2.8.2 Henan Province

The Zhengzhou Fruit Research Institute of the Chinese Academy of Agricultural Science (CAAS) in Zhengzhou released two selections in 1988: 'Huaguan' ('Golden Delicious' × 'Fuji') and 'Huashuai' ('Fuji' × 'Starkrimson'). Both have been noted for their quality and storage life.

3.2.8.3 Liaoning Province

There are three programmes in this province, with the Liaoning Fruit Research Institute having the largest apple-breeding programme in China. One of their objectives is to produce a new cultivar with all the advantages of 'Fuji' but none of the disadvantages. 'Golden Delicious 463', a russet-resistant induced sport, is their best-known introduction. Shenyang Agricultural University released 'Hanfu', a hybrid of 'Dongguang' × 'Fuji'. This cultivar is known for its hardiness and high eating quality. The Research Institute of Pomology (CAAS) released 'Qiojin' in 1975.

3.2.8.4 Shaanxi Province

The Shaanxi Fruit Research Institute at Yangling released 'Quinguan', a hybrid of 'Golden Delicious' × 'Jiguan', in 1970.

3.2.8.5 Shandong Province

The Shandong Fruit Research Institute is at Tai-an.

3.2.8.6 Xinjiang Autonomous Region

The Kueitun Fruit Research Institute released 'XinShuai' in 1985.

3.2.9 Czech Republic

The programme at the Research and Breeding Institute of Pomology in Holovouzy began in 1951. It has emphasized the use of polygenic resistance to scab from old or lesser-known cultivars. Disease resistance and modification of plant form are stressed. Six cultivars with scab tolerance have been named: 'Angold', 'Julia', 'Klara', 'Nabella', 'Produkta' and 'Zuzana' (Blazek and Paprstein, 1994). Other releases important in the Czech Republic include 'Jarka', 'Julia', 'Resista' and 'Selena'.

3.2.10 England

This programme emphasizes high quality, long storage, the ability to compete with imported fruit and resistance to mildew and apple scab. Apples similar to 'Cox's Orange Pippin' were emphasized, but now diverse types are sought. Ten cultivars have been named since 1971. 'Fiesta', a 'Cox's Orange Pippin' × 'Idared' hybrid released in 1984, is well known. 'Saturn' (PRI 1235 × 'Starkspur Golden Delicious') is a recent release. Six columnar (reduced branching) cultivars have been named: 'Maypole', 'Telamon', 'Tuscan' and 'Trajan' (Tobutt, 1985) and 'Charlotte' and 'Obelisk' released in 1991. Molecular markers are being developed for pre-selection at a juvenile stage (Evans, 1999).

3.2.11 Finland

Breeding is conducted at the Agricultural Research Centre Institute of Horticulture in Pikkio.

3.2.12 France

3.2.12.1 Institut National de la Recherche Agronomique, Angers

Objectives include resistance to pests and diseases, reduction of orchard labour requirements and improved fruit quality. Several cultivars have been released for processing and juice production, including 'Jurella', 'Judaine', 'Judor' and the scab-resistant 'Chanteline'. Other releases include INRA Belchard® 'Chantecler' ('Golden Delicious' × 'Reinette Clochard'), INRA Querina® 'Florina', a complex hybrid that is resistant to scab and to rosy apple aphids, released in 1985, and INRA 'Baujade', a scab-resistant green apple with 'Granny Smith' in its pedigree, released in 1992. 'Initial' is a new triploid, scab-resistant cultivar from 'Gala' × 'Redfree' that ripens about 1 week before 'Gala' (Laurens *et al.*, 2000). INRA Perpetu® 'Evereste', an ornamental crab apple, has also been released. Apple breeding at INRA also emphasizes the genetic modification of plant form. The aim is to have a branching pattern that balances vegetative and reproductive growth, reducing pruning costs and reducing the tendency towards biennial bearing (Lauri *et al.*, 1997).

3.2.12.2 Commentary

Delbard International Nursery has a private breeding programme. Cultivars released include: 'Delbarestivale'® 'Delcorf' ('Jongrimes' × 'Golden Delicious'), 'Delbard'® 'Jubilee' ('Golden Delicious' × 'Lundbytrop'), 'Cybele'® 'Delrouval' ('Delcorf' × 'Akane'), 'Delearly' ('Goldspur' × 'Stark's Earliest') and 'Harmonie'® 'Delorina' ('Grifer' × 'Florina'). Two of their cultivars are also being marketed in the USA. 'Delblush' (cv. 'Grifer') is a 'Golden Delicious' × 'Blushing Golden' hybrid called 'Tentation' in France. It received US Plant Patent (USPP) no. 10,276. 'Regali'® 'Delkistar' ('Kidds' Orange Red' × 'Bisbee Red Delicious') received USPP no. 11,213.

3.2.13 Germany

3.2.13.1 Ahrensburg

Apple breeding at the Federal Centre for Breeding and Research on Cultivated Plants started in 1976, but was moved to Dresden-Pillnitz in 1999 (see below). The goal was to develop high-quality cultivars with resistance to scab, mildew and *Nectria* canker. Releases include 'Ahrina' (1989) and the scab-resistant (V_p) cultivars 'Gerlinde', 'Ahrista' and 'Ahra'. 'Ahra' also has low susceptibility to canker.

3.2.13.2 Dresden-Pillnitz

Apple breeding started in 1928 in Munchenberg and was moved to Dresden-Pillnitz in 1971. The 'Pi' cultivar series ('Pi' for Pillnitz) were bred for high quality, regular high yields and low susceptibilities to diseases. Ten 'Pi' cultivars have been named, including 'Piros', 'Pilot', 'Pingo' and 'Pirella'. 'Corail', originally named 'Pinova', a hybrid of 'Clivia' × 'Golden Delicious', is of interest in Europe and in the USA. The 'Re' series is characterized by good fruit quality, high yield and different sources of scab resistance. Fourteen 'Re' cultivars have been named: 'Remo', 'Rewena', 'Rebella' and 'Reanda' have resistance to scab, mildew and fire blight (Fischer, 2000a,b).

3.2.14 Greece

The National Agricultural Research Foundation Pomology Institute in Naoussa is incorporating both monogenic and polygenic resistance. The local cultivar 'Firiki' has been used in breeding. 'Naoussa' and 'Makedoni' were released from crosses made in 1973.

3.2.15 Hungary

Apple breeding started in 1972 at the University of Horticulture and Food

Industry in Budapest. The programme was modified in 1984 and 1991 (Toth *et al.*, 1994). Quality, local adaptation and resistance to multiple diseases and pests are priorities. Four hybrids of 'Jonathan' × 'Egri Piros' were released from 1985 to 1993.

3.2.16 India

Sharma and Kumar (1994) reviewed fruit-crop improvement in India and detailed 12 apple cultivars released. They suggested that the limited success of fruit breeding in India might be due to the lack of continuity, specific gene sources and misdirected strategy

3.2.17 Italy

3.2.17.1 Bologna

The breeding programme at the University of Bologna was initiated in 1976 and scab resistance was added in 1981. Objectives emphasize scab resistance, low susceptibility to mildew, spur or compact habit and high fruit quality (Sansavini and Ventura, 1994). 'Prime Red', a hybrid of 'Prima' × 'Summered', was named in 1999

3.2.17.2 Forli

The Istituto Sperimentale per la Frutticoltura programme at Forli started in 1980 to develop improved dessert cultivars with resistance to scab and well adapted to the Po Valley

3.2.17.3 Trento

Apple breeding at the Trento section of the Experimental Institute of Fruit Culture started in 1974. Quality and pyramiding of resistance are important objectives. Seven scab-resistant cultivars were released from 1997 to 1999: 'Giongo', 'Red Earlib', 'Golden Mira', 'Brina', 'Nova', 'Summerfree' and 'Golden Orange'. The last three cultivars are all hybrids of PRI 1956-6 × 'Ed Gould Golden'.

3.2.17.4 Ferraro

Private breeding by the nursery consortium Consorzio Italiano Vivaisti (CIV) has resulted in the naming of 'Rubens' and 'Giotto', both hybrids of 'Gala' × 'Elstar'.

3.2.18 Japan

Bessho *et al.* (1993) reviewed the status of apple breeding and genetic analysis in Japan. The apple industry in Japan developed following the importation of 75 cultivars from America in 1871. 'Ralls Janet' and 'Jonathan' were two of the cultivars imported. Apple breeding started at the Aomori Apple Experiment Station in 1928. In 1939 a programme was started at the Morioka Branch of the Fruit Tree Research Station. There are seven prefectural research stations and a national research station conducting apple breeding.

Research in Japan focuses not only on cultivar development, but on all facets of genetic improvement. Resistance to *Alternaria* blotch has been identified and the inheritance detailed. Resistance to apple chlorotic leaf-spot virus (ACLSV) and apple stem-pitting virus (ASPV) was determined to be controlled by two recessive genes. Other studies have provided information on the inheritance of tree habit, fruit colour, prevalence of burr knots and *Valsa* canker resistance (Bessho *et al.*, 1993).

3.2.18.1 Aomori Prefecture

The Aomori Apple Experiment Station in northern Japan has released many cultivars, including the self-compatible cultivar 'Megumi' in 1950 and 'Mutsu' in 1949, 'Sekaiichi' in 1974, 'Tsugaru' in 1975, 'Kitanosachi' in 1979, 'Hokuto' and 'Natsumidori' in 1983 and 'Mellow' in 1990. 'Aori 9', a hybrid of 'Akane' × 'Orin', which is reported to be self-thinning, will be named (Kon *et al.*, 2000)

3.2.18.2 Akita Prefecture

The Akita Fruit Tree Experiment Station named 'Senshu' in 1983 and 'Akita Gold' ('Golden Delicious' × 'Fuji') in 1990.

3.2.18.3 Gunma Prefecture

The Gunma Agricultural Research Centre released two hybrids of 'Golden Delicious' by an unknown pollen parent: 'Akagi' released in 1973 and 'Yoko' released in 1981. They also named 'Sinsekai', a hybrid of 'Fuji' × 'Akagi', in 1988, and 'Gunma Meigetsu', a hybrid of 'Akagi' × 'Fuji', in 1991.

3.2.18.4 Fukushima Prefecture

Breeding at the Fukushima Fruit Tree Experiment Station started in 1987, with the goal of developing cultivars suited to Japan's warmer areas.

3.2.18.5 Hokkaido Prefecture

The Hokkaido Prefectural Agricultural Experiment Station released 'Hacnine', a hybrid of 'Fuji' × 'Tsugaru', in 1984.

3.2.18.6 Iwate Prefecture

The Iwate Horticultural Experiment Station released 'Kio', a hybrid of 'Orin' × 'Hatsuaki', in 1992.

3.2.18.7 Morioka

Apple breeding started in 1939 at the Apple Research Centre at the National Institute of Fruit Tree Science (NIFTS). Sixteen cultivars have been named since 1952. Fruit quality, storage ability and disease resistance are high priorities. There have been three stages to the programme. 'Fuji' released in 1962, 'Akane' in 1970 and 'Hatsuaki' in 1976 were first named. The second phase resulted in 'Kitakami' in 1981, 'Himekami' in 1985 and 'Iwakami' in 1985. The third programme released 'Sansa' in 1986 and 'Kizashi' in 1991. 'Chinatsu', a hybrid of 'Akane' × 'Earliblaze', and 'Kitaro', a hybrid of 'Fuji' × 'Hatsuaki', were released in 1997. 'Kotora', a sib of 'Kitaro', was named in 1998 (Soejima *et al.*, 2000).

3.2.18.8 Nagano Prefecture

The Nagano Fruit Tree Experiment Station established apple breeding in 1970. Releases include 'Takane' in 1982 and Nagano Apple (NA) selections NA-10 ('Fuji' × 'Tsugaru'), NA-12 ('Tsugaru' × 'Vista Bella') and NA-15 ('Golden Delicious' × 'Senshu'). Scab-resistance breeding was added in 1988. 'Akane' and 'Alps-Otome', a sweet crab apple, are sources of scab resistance.

3.2.18.9 Private breeders

There are also about ten private breeders in Japan who have released many cultivars, including: 'Akibea', 'Alps Otome', 'Kanki' (USPP no. 11,508), 'Kinsei', 'Kogetsu', 'Michinoku', 'Miki Life' (USPP no. 11,511), 'Orin' and 'Scarlet'.

3.2.19 Korea (South)

Breeding and biotechnology of apple cultivars and rootstocks is overseen by the National Horticultural Research Institute, Rural Development Administration. Apple breeding is carried out at the Taegu Apple Research Institute. Cultivars released include: 'Hwahong', a hybrid of 'Fuji' × 'Sekaiichi', which ripens late in the season and has a long storage life; 'Hongro' ('Spur Earliblaze' × 'Spur Golden Delicious'), named in 1988; 'Kamhong' ('Spur Earliblaze' × 'Spur Golden Delicious') and 'Chukwang' ('Fuji' × 'Mollie's Delight'), selected in 1992; and 'Seokwang', selected in 1996, an early-season apple with an attractive colour and aromatic flavour.

3.2.20 Latvia

The Dobeles Horticultural Plant Breeding Experimental Station is studying local genetic resources and local cultivars that may have been influenced by western and Russian cultivars. Twenty-eight cultivars have been analysed for their breeding value. The area is limited by low temperature periods of -30 to -35°C and by a short growing season of only 135-140 days (Ikase, 1999).

3.2.21 Lithuania

Breeding at the Lithuanian Institute of Horticulture in Kaunas also involves study of the inheritance of tree characteristics (height, diameter, branch number and internode length) and winter-hardiness (Gelvonauskis, 1999).

3.2.22 Mexico

The breeding programme at the Colegio de Postgraduados, Fruticultura-IREGEP (Institute of Genetic Resources and Productivity) has as an objective the development of low-to medium-chill cultivars

3.2.23 The Netherlands

Breeding is at the Centre for Plant Breeding and Reproduction Research (CPRO-DLO) in Wageningen. From crosses made between 1948 and 1963, six selections were named, with 'Elstar' being the most important. From 1964 to 1988 crosses, 'Elan' and 'Elise' CPRO® were named. Crosses in the late 1970s emphasized scab resistance and resulted in the naming of the scab- and mildew-resistant cultivar 'Ecolette CPRO®', a hybrid of 'Elstar' × 'Prima', in 1995. The next release, 'Santana CPRO®', a hybrid of 'Elstar' × 'Priscilla', is resistant to scab and has good resistance to European canker but is very susceptible to mildew. A sweet apple from 'Idared' × 'Elstar' will be named 'Bellida'. The web address is <http://www.plant.wag-ur.nl/>

3.2.24 New Zealand

McKenzie (1983) reviewed apple breeding from its 'unofficial' start in New Zealand over 100 years ago to the official start of a national programme at a government research station in Havelock North in 1969. Research scientists of the Department of Scientific and Industrial Research produced three very large families with 40,000 seedlings per family. 'Gala', 'Splendour' and 'Braeburn' were often parents of the 10,000–20,000 seedlings

produced annually. 'Joy' and 'Festival' were selected in the 1970s and commercialized in several countries. Selections from 'Gala' × 'Splendour' have been tested extensively in New Zealand and are being evaluated under non-distribution agreements in several countries. These include 'Pacific Rose' (Plate 3.3), 'Southern Snap', 'Sci Early' and 'Sci Red' (Plate 3.4). Disease and insect resistance are also being stressed (White and Bus, 1999). Information on mapping, transformation, disease and insect resistance and germplasm development is found at <http://www.hortresearch.cri.nz/>

3.2.25 Norway

Breeding at the Ullensvang Research Centre in Hermansverk emphasizes the development of improved early-ripening cultivars. Four hybrids of 'Katja' × 'Buckley Giant' were introduced: 'Nanna', 'Siv', 'Eir' and 'Idunn'.

3.2.26 Poland

3.2.26.1 Skierniewice

Zurawicz and Zagaja (1999) reviewed breeding at the Research Institute of Pomology and Floriculture at Skierniewice. Three cultivars have been released: 'Fantazja' ('McIntosh' × 'Linda'), 'Alwa' ('Macoun' open-pollinated), and 'Lodel' ('Lobo' × 'Red Delicious'). Two selections, 'Redkroft' and 'Ligol' ('Linda' × 'Golden Delicious'), are in final testing.

3.2.26.2 Warsaw

This programme at the Warsaw Agricultural University started in 1975. 'Witos', 'Sawa' and 'Alka' are cultivars that have been released. 'Sawa', a hybrid of 'Fantazja' × 'Primula', is considered to be a very good-quality, scab-resistant apple.

3.2.27 Romania

Braniste (1997) reviewed apple breeding in Romania, which started in 1948 in

Bucharest. Hybridizations are made in four locations. Twenty-three cultivars have been named, including 'Frumos de Voinesti', 'Delios de Voinesti', 'Rosu de Cluj' and 'Aromat de vara'. The scab- and mildew-resistant 'Romus 1', 'Romus 2' and 'Romus 3' were released in 1984 and 'Pionier', 'Voinea' and 'Generos' were named in 1985 and 1986

3.2.28 Russia

There are at least nine apple-breeding programmes in Russia, with many other programmes being conducted as part of programmes within botanic gardens. While most publications are in Russian, English abstracts of the breeding objectives and releases are available in some databases. Durable resistance to scab and powdery mildew, adaptation to adverse winter conditions, increased ascorbic acid content of the fruit, reduced tree vigour and compact habit and greater use of local cultivars and wild species are emphasized. It is difficult to detail specific programmes, but some of the locations include the following

3 2 28 1 *The All-Russian Research Institute of Horticultural Breeding in Orel*

Dr E.N. Sedov is the apple breeder. This programme stresses high productivity, winter-hardiness, immunity to scab, high ascorbic acid (vitamin C) content and breeding for compact habit. *Malus sylvestris*, *Malus coronaria* and 'Kola' crab apple have been used for improving vitamin C content. The use of polyploids in breeding has been emphasized since 1970, especially crosses of 4x and 2x

3 2 28 2 *The All-Russian Research Institute of Horticulture (VNIIS) and All-Russian Research Institute of Genetics and Breeding of Fruit Plants in Michurinsk*

The cultivar 'Skala' resulted from a cross of I.V. Michurin's cultivar × 'Prima'. 'Skala' is scab-resistant (V_f) with large fruit and high vitamin C content.

Programmes also exist at the All-Russian Breeding and Technological Institute of Horticulture and Nursery in Moscow and the Research Institute of Horticulture of Siberia in Barnaul.

3.2.29 South Africa (Republic of)

The Breeding and Evaluation Division of Agricultural Research Council Infruitec/Nietvoorbij emphasizes the development of high-quality, long-storing apple cultivars to give the South African industry a competitive advantage. Development of locally adapted cultivars is aided by studies of variation in winter chilling requirements and prolonged dormancy symptoms. Breeding was started in 1955 and the apple cultivars 'Drakenstein' and 'Gold Gift' were released. Scab-resistance breeding started in 1994. 'African CarmineTM' is a 1999 release. Information on the programme is available at <http://www.arc.agric.za/lnr/institutes/niet/breeding/projects.html/>

3.2.30 Spain

The Centro de Investigacion Aplicada y Tecnologia in Villaviciosa has as an objective the genetic improvement of cider apples.

3.2.31 Sweden

The Department of Horticultural Plant Breeding at the Swedish University of Agriculture in Balsgard released 'Alice' in 1963, 'Katja', 'Aroma', 'Sylvia', 'Kim' and 'Amorosa' ('Red Aroma'). Home-garden cultivars include the winter-hardy 'Rodluvan'. Information on the programme is at <http://www.hvf.slu.se/> Objectives include winter-hardiness, compact growth, good quality, resistance to diseases, high yield and long shelf- and storage-life.

3.2.32 Switzerland

The Swiss Federal Research Station in Wädenswil has released the cultivars

'Maigold', 'Goro', 'Arlet', 'Iduna' and 'Marina' (Kellerhals and Meyer, 1994). Scab-resistance breeding started in 1986 in cooperation with Horticulture Research International (HRI) in the UK and several other institutions, and this has resulted in the naming of 'Ariwa', a scab- and mildew-resistant cultivar, bred in cooperation with HRI. Information on the programme is at <http://www.admin.ch/sar/faw/>

3.2.33 Yugoslavia

3 2 33 1 Novi Sad

The programme at the Faculty of Agriculture, Institute for Fruit Growing and Viticulture started in 1985, with the breeding of columnar apples added in 1987 (Ognjanov *et al.*, 1999). Objectives include preservation of germplasm, breeding for multiple resistance using polygenic and monogenic sources and the production of cultivars suited for the home market, for use as pollinators and as ornamentals

3 2.33 2 Cacak

The Fruit and Viticulture Research Centre at Cacak is part of the Agricultural Research Institute, Serbia. Apple breeding started in 1946. Since 1980 resistance breeding has been emphasized. Two hybrids of 'Starking Delicious' × 'Jonathan' have been named: 'Cacanska Pozna' in 1971 and 'Cadel' in 1984.

3.3 Natural and Induced Variation: Mutations and Sports

Apples are prone to limb or whole-tree mutations for enhanced fruit surface colour, for spur-type growth habit and occasionally for russet and ploidy differences (Pratt, 1983). Cultivars differ in their tendency to mutate, with 'McIntosh', 'Delicious', 'Jonagold', 'Gala' and 'Fuji' being very prone to mutation. Yet 'Empire', derived from the frequently mutating 'McIntosh' and 'Delicious', has only produced three sports

to date. 'Golden Delicious' also has non-russetting sports

To be most useful, mutations should be periclinal mutations, a solid mutation that includes all of LI and/or LII layers. If the mutation includes the LII layer, where the gametes are formed, then the mutation will also be useful in breeding. One example is the columnar, or reduced branching, habit of 'Wijcik McIntosh', which is conferred by a single dominant gene, *Co* (Lapins, 1974). This sport is being used in crosses to study branching and to develop trees with modified plant form.

Sports that are initially mericlinal or sectorial can be stabilized. However, periclinal chimeras are sometimes unstable and may revert back to the original cultivar, as exemplified by the 'MacSpur' mutation of 'McIntosh' (Embree *et al.*, 1991). Pratt (1983) reviewed somatic selection and chimeras in fruit crops and discussed the diploid-tetraploid sports in apple and the development of a disbudding technique to determine the inner phenotype of apple sports.

Mutation breeding of apples was once popular, but declined in use because of the high frequency of chimeras and undesirable or unstable forms (Lapins, 1983; Van Harten, 1998). Mutation breeding emphasized compact types, non-russetting sports and sports with more fruit colour. Lacey and Campbell (1987) reviewed the selection, stability and propagation of mutant apples and the tests used to determine the nature of the mutation. These methods of selecting and screening chimeras in mutation breeding may also need to be used in transgenic apple, where the possibility of chimeras of transformed and non-transformed tissues must be considered (Ko *et al.*, 1998).

White *et al.* (1994) studied red colour changes following irradiation of 'Royal Gala' apple scions. They found a wide variation among clones, but a small range of variation within clones, consistent with the hypothesis that the level of red colour expression is controlled by a multiple allelic series at the loci governing red colour. Naturally occurring mutations of this multiple allelic series were proposed.

Concerns have been raised that redder sports appear to have a loss of flavour, in contrast to the original parental clone. Fellman *et al.* (2000) reviewed the occurrence and biosynthesis of acetate esters, which are the volatile compounds that impart the fruity flavour and aroma associated with apples. They found that higher-colouring strains of 'Delicious' had lower aroma content. This suggests that, when we select within a clone for higher pigmentation, quality may suffer.

Molecular methods to differentiate among sports of a cultivar would be highly desirable for the patenting, identification and protection of new sports. However, since the genetic change is very small, current methods have not proved useful. Pancaldi *et al.* (1999) used a randomly amplified polymorphic DNA (RAPD) strategy called template mixing for the molecular analysis of mutant clones, but this did not result in the additional bands (heteroduplexes) that are expected if the primers are able to amplify the mutated DNA region. Tignon *et al.* (2000) used amplification restriction-fragment length polymorphism (AFLP) to examine within-cultivar variation, but found that it could not be used for a secure identification of mutant cultivars.

3.4 Genetics and Inheritance of Traits

Alston *et al.* (2000) updated the *Malus* gene list to include 145 genes, with 29 involved in pest or disease resistance. Similar lists and discussions are found in Brown (1992) and Janick *et al.* (1996). Gene discovery is increasing as sequences from other species are being used to investigate *Malus*.

Genetic research on plant architecture, spurriness, bearing habit and regularity of production is also of high priority. Tobutt (1994) crossed cultivars with apetalous flowers – 'Wellington Bloomless' and 'Spencer Seedless' – with four columnar selections and determined that the gene *ape* for apetalous was recessive. Apetalous cultivars tend to set fruit parthenocarpically. Apetalous parthenocarpic selections would have a reduced need for pollination and, with less seed production, might be less prone to biennial bearing.

3.4.1 Heritability studies

Heritability estimates provide breeders with an indication of the potential for mass selection in improving a trait. Traits with high heritability are more amenable to improvement, since the appearance (phenotype) is a good indication of the breeding value (genotype). Tancred *et al.* (1995) determined that the heritability of ripening dates is high. Durel *et al.* (1998) calculated narrow-sense heritabilities for apple traits, using large unbalanced data sets. Heritability values around 0.35–0.40 were obtained for fruit size, texture, flavour, juice content, attractiveness and russetting. Higher heritability values were obtained for vigour, characterized by trunk circumference, and powdery mildew resistance (0.68). Currie *et al.* (2000) used 82 open-pollinated families to analyse fruit shape and reported a combined-site heritability of 0.79 for fruit aspect, best predicted by the fruit length/width ratio ($R^2 = 0.97$). Oraguzie *et al.* (2001) estimated narrow-sense heritabilities for 19 traits in several sites, including fruit ribbing (0–0.13), fruit russet (0.05–0.58), fruit overcolour (0.34–0.40) and fruit weight (0.27–0.90).

3.5 Disease Resistance: Present Status and Future Directions

3.5.1 Apple scab (*V. inaequalis* (Cooke) Wint.)

The discovery, characterization and use of genes for resistance to apple scab demonstrates the importance of diversifying sources of resistance. Williams and Kuc (1969) summarized both qualitative and quantitative sources of resistance to apple scab. Although six genes for scab resistance were available, breeders concentrated primarily on V_1 . The V_m gene from *Malus micro-malus* and *Malus atrosanguinea* 804 was susceptible to race 5, genes from 'Russian seedling R12740-7A' (V_2 and V_3) were known to have differential resistance and the resistance gene V_{b7} from *Malus baccata* *jackii* was not used by many programmes. The danger of concentrating on one source of

qualitative resistance became evident in 1993 with the discovery of race 6. Race 6 induced scab on nearly all V_f selections, but did not infect *Malus floribunda* 821, one of its selected F_2 progeny (F_2 26829-2), 'Granny Smith', *M. baccata* jackii (V_{bf}) and 'Russian seedling R12740-7A' (V_r , V_x) (Parisi and Lespinasse, 1999). The discovery of race 7 and the interaction between race 6 and race 7 with the original source of resistance, *M. floribunda* 821, suggested the existence of a second dominant gene, independent of V_f (Benaouf and Parisi, 2000). This gene was named V_{fh} because it induced a hypersensitive response. This finding supports theories that V_f resistance was more complex than it being dependent only on a single gene. Results from race 7 identified another dominant gene, V_{gr} responsible for the resistance of 'Golden Delicious' to strain 7.

Breeders need to pyramid sources of resistance and to use molecular markers in pyramiding to ensure that more than one gene for resistance is present. We need to have a better understanding of differential reactions (Gessler and Blaise, 1994) and of the resistance in 'Antonovka' (V_a and polygenic) and in 'Jonsib'. We need to characterize and use polygenic or partial resistance and/or the natural low susceptibility of old cultivars, new cultivars and advanced selections. The use of polygenic resistance will require modifications of existing protocols and examination of factors such as the influence of scab inoculum concentration in screening for quantitative resistance (Lateur *et al.*, 2000).

Durable Apple Resistance in Europe (DARE) is a project funded by the European Union to detect and characterize durable sources of resistance in local European cultivars. Nine institutions participate in the project. Lespinasse *et al.* (2000) summarized the work in progress. DARE focuses on durable resistance to scab and powdery mildew. Goals include: (i) characterization of resistance of cultivars; (ii) assessment of the pathogenicity and variability of the two fungi; (iii) genetic dissection of partial resistance; (iv) development of new breeding strategies; and (v) market study and consumer preference for new resistant culti-

vars. Information on DARE is available at <http://www.inra.fr/Angers/DARE/>. Polygenic resistance in 'Antonovka', 'Discovery', 'James Grieve', 'Dulmener Rosenapfel' and the old Italian cultivars 'Durello di Forlì' and 'Renetta Grigoia di Torriana' will be studied.

3.5.2 Powdery mildew (*P. leucotricha* (Ell. & Ev.) Salm.)

Many commercial cultivars being used in breeding, such as 'Ginger Gold', 'Honeycrisp' and 'Goldrush', are highly susceptible to powdery mildew, making parental and progeny selection for resistance important. Breeding for resistance to powdery mildew has been difficult due to a poor understanding of the races and their geographical locations and often a poor correlation between seedling (i.e. juvenile plant) reaction to infection and that of mature plants.

There are both qualitative and quantitative sources of resistance in *Malus*. Knight and Alston (1968) first proposed single gene control of resistance, but later two different genes plus modifiers were proposed: Pl_1 from *Malus* × *robusta* and Pl_2 from *Malus* × *zumii* Rehd. In 1977, Dayton identified an open-pollinated seedling from 'Starking Delicious' as highly resistant. The seedling's pollen parent was believed to be a *Malus* species. This seedling was designated mildew-immune seedling (MIS). Alston *et al.* (2000) proposed the designation $Pl-m$ for this resistance. Alternatively, Korban and Riemer (1990) examined segregation among 14 progenies for mildew reaction and indicated that mildew resistance was polygenically controlled in this material with additive gene effects.

3.5.3 Fire blight (*Erwinia amylovora* (Burrill) Winslow)

Many popular scion cultivars and rootstocks are highly susceptible to this bacterial pathogen. Therefore, the use of genetic resistance by traditional breeding and by biotechnology is a goal of many programmes. The

scion cultivar 'Liberty' is a good source of resistance and may also be used as a control cultivar to assess resistance in transgenic lines.

Gardner *et al.* (1980a) evaluated *Malus* species and clones for resistance and found that the small-fruited Asian species, especially *Malus sieboldii*, were outstanding sources of resistance. There were very few domestic cultivars with high resistance and intraspecific variation was noted. They cautioned that screening and inoculation based on young seedlings might not reflect the susceptibility of older shoots. The inheritance of resistance was studied. There was 90% mortality in crosses of susceptible $\times$ susceptible. Resistant $\times$ susceptible yielded few resistant offspring and resistant $\times$ resistant still produced some highly susceptible seedlings, suggesting quantitative control of resistance. In crosses of the highly resistant *M. $\times$ robusta* No. 5 $\times$ *Malus $\times$ sublobata* PI286613, resistance was suggested to be controlled by a few genes (Gardner *et al.*, 1980b). Polygenic control of resistance was also suggested in a study of eight interspecific and intraspecific crosses. *Malus prunifolia* var. *xanthocarpa* and *M. prunifolia* var. *microcarpa* were good sources of resistance (Korban *et al.*, 1988).

Evaluation of greenhouse-grown seedlings inoculated with a mixture of strains of the bacteria was found to be a better predictor of field susceptibility than evaluation with single strains (Norelli *et al.*, 1986). With the discovery of differential susceptibility, Norelli *et al.* (1986, 1987) cautioned that progenies must be inoculated with strains that are representative of the complete range of differential virulence when breeding for resistance.

Chevreau *et al.* (1998) examined four somaclonal variants of 'Greensleeves' for resistance and found that *in vivo* tests were unreliable due to high variability, that greenhouse inoculation was more reliable but overrated resistance and that field inoculation was the most severe test. Transformation of apple with lytic peptides to confer resistance to fire blight has been successful (Norelli *et al.*, 1999). Transgenic lines of 'Royal Gala' and M.7 rootstock with the gene encoding attacin E resulted in a significant increase in resistance to fire blight.

3.6 Other Traits

3.6.1 Quality

The improvement of fruit quality is one of the most important breeding objectives, but genetic manipulation is hampered by the complexity of the topic, the influence of the environment and the lack of measurements that are quantitative rather than subjective. The definition of quality will vary depending on the programme and market requirements, but flavour, texture (crispness and firmness) and juiciness are three components of interest to most breeders. Genetic improvement of postharvest quality is also important.

Apple flavour, including taste, aroma, off-flavours, primary and secondary volatiles and correlations between instrumental and sensory analysis, was reviewed by Yahia (1994). He suggested focusing on odour-active volatiles as a key to future molecular manipulation.

Many programmes are using sensory testing as part of their evaluations. Hampson *et al.* (2000a) detailed the use of sensory evaluation as a selection tool in apple breeding. They determined that a minimum panel size of 11 was necessary to obtain statistical discrimination of one point on a zero-to-nine scale. Crispness was found to account for 90% of the variation in texture liking. Perceived sweetness and sourness were better predictors of liking than fruit Brix and titratable acid. Deslauriers *et al.* (1999) used DSA to define and quantify the sensory properties of apple and used statistical programmes to select genotypes most similar to a target cultivar, such as a popular processing type, but with enhanced productivity. The use of sensory assessment also proved valuable in detecting quantitative trait loci (QTL) representing different attributes of fruit texture (King *et al.*, 2000). Significant QTL were detected on seven linkage groups. Magness-Taylor penetrometer readings, stiffness by acoustic resonance and sensory descriptors assessed by a trained panel were the instrumental measurements used.

3.6.2 Nutrition

Increasing the ascorbic acid or vitamin C concentration in apples has long been a goal in apple breeding. While most cultivars contain from 5 to 10 mg ascorbic acid g⁻¹, cultivars with much higher concentrations (20–50 mg g⁻¹) have been documented. While vitamin C concentration is important, the role of other antioxidants is also of interest and is likely to be a new area for genetic improvement. Eberhardt *et al.* (2000) demonstrated that 100 g of fresh apples have an antioxidant activity equivalent to 1500 mg of vitamin C. Apple phytochemicals, phenolic acids and flavonoids significantly enhance the antioxidant properties and are amenable to genetic improvement.

3.6.3 Reduction of flesh browning

Genetic reduction of apple flesh browning is also a breeding objective. For the fresh-cut slice market, cultivars will need to have low levels of polyphenol oxidase and sufficient ascorbic acid and to maintain their crispness and firmness. Transgenic approaches to reduced browning are also being tested.

3.6.4 Allergenicity

Research on the allergenicity of apples has expanded. Puhlinger *et al.* (2000) found that the promoter for the major allergen Mal d1 is stress- and pathogen-induced. Breeders need to ensure that new cultivars are not higher in allergenicity and need to explore prospects of breeding apples with lower allergenicity.

3.7 Markers and Genetics

The ability to use molecular markers for pre-selection at the seedling stage, prior to field planting, is of great importance. The ability to prescreen reduces land and greenhouse requirements, saves money and results in a higher percentage of desirable seedlings being planted in the field.

3.7.1 Isozymes

Isozymes were the first markers to be used in apple breeding. They have been used for identification of cultivars, for estimating genetic diversity in germplasm collections and to confirm or refute suspected parentage. Chyi and Weeden (1984) used isozymes to determine that the female parent supplied the unreduced diploid gamete in several triploid cultivars. Weeden and Lamb (1987) studied isozyme polymorphism in nine enzyme systems and identified four linkage groups. Close linkage of glutamate oxaloacetate transaminase (Got-1) and the S incompatibility locus was reported (Manganaris and Alston, 1987). Manganaris and Alston (1988) also found that the acid phosphatase gene ACP-1 was linked with the endopeptidase gene ENP-1 and the pale green lethal gene, *l*. In 1994, Manganaris *et al.* reported that the isozyme locus *Pgm-1* was tightly linked to *V_f* scab resistance. Advances continue to be made. Alston *et al.* (2000) reviewed research on 69 isozymes in apple.

3.7.2 Scab resistance

The amount of research focused on the identification and development of markers for the *V_f* gene is extensive. Only the most recent studies will be discussed. Patocchi *et al.* (1999) used markers to fine-map the *V_f* region. Xu and Korban (2000) used AFLP markers for saturation mapping of *V_f* and then sequence-characterized amplified regions (SCARs) were developed from these AFLP markers (Xu *et al.*, 2001). These are prerequisites for map-based cloning. Markers have also been developed for the *V_m* region from *M. atrosanguinea* 804 (Cheng *et al.*, 1998). Research on markers for the other genes for scab resistance is progressing in several laboratories.

3.7.3 Powdery mildew

Molecular markers for the resistance genes *Pl₁* from *M. × robusta* (Markussen *et al.*, 1995), *Pl₂* from *M. × zumi* Rehd. (Dunemann *et al.*,

1999) and Pl_w from 'White Angel' (Batlle and Alston, 1996) are being used in marker-assisted selection.

3.7.4 Insect resistance

Markers have been developed for resistance to the rosy leaf-curling aphid (*Dysaphis devecta* Wlk.) (Roche *et al.*, 1997a,b) and to woolly apple aphid (*Eriosoma lanigerum* Hausmn.), an important pest in breeding rootstocks (Bus *et al.*, 2000).

3.7.5 Incompatibility alleles

The self-incompatibility system in apple is well known, but until recently the number of *S* alleles involved and the extent of cross-incompatibility was not known. The cloning and molecular analysis of two self-incompatibility alleles from apple (Broothaerts *et al.*, 1995) was followed by the development of a molecular method for *S*-allele identification in apple based on allele-specific PCR (Janssens *et al.*, 1995). The alleles *S*2, *S*3, *S*5, *S*7 and *S*9 were identified and used to genotype several cultivars, including 'Idared' (*S*3*S*7), 'Fiesta' (*S*3*S*5), 'Jonathan' (*S*7*S*9), 'Elstar' (*S*3*S*5), 'Gala' (*S*2*S*5) and 'Golden Delicious' (*S*2*S*3). Sakurai *et al.* (1997, 2000) used this method to genotype Japanese and American apple cultivars and advanced selections. Six additional *S* alleles were sequenced: *S*4, *S*24, *S*26, *S*27, *S*d and *S*f (Sassa *et al.*, 1996; Katoh *et al.*, 1997; Verdoodt *et al.*, 1998). *S* genotyping has raised questions of paternity in that several cultivars have *S* alleles different from those predicted by their parentage.

S-allele genotyping has also been used to assess homozygosity in shoots obtained through haploid induction by screening *in vitro* shoots for single *S* alleles as opposed to *S* alleles of a parent whose pollen was irradiated and used to stimulate parthenogenic development (Verdoodt *et al.*, 1998). Van Nerum *et al.* (2000) transformed 'Elstar' with an *S* allele in the sense or antisense direction and analysed lines for self-fertility. Fluorescent microscopy confirmed that some

lines appeared to have the incompatibility mechanism switched off, as evidenced by pollen-tube growth.

3.7.6 Other traits

Markers have been identified for many traits, including fruit skin colour (Cheng *et al.*, 1996), columnar habit (Hemmat *et al.*, 1997) and fruit acidity (malic acid concentration) (Conner *et al.*, 1997). Conner *et al.* (1998) used RAPDs to estimate the position and effect of QTL affecting juvenile tree growth and development and found that a large number of traits had significant variation associated with the map position of the dominant columnar gene, *Co*.

3.7.7 Microsatellites/simple sequence repeats (SSRs)

SSRs, short tandem repeats of one to six base pairs, have been used in cultivar identification and genetic analysis and to reveal identities, genetic diversity and relationships in a core subset collection. Guilford *et al.* (1997) used SSRs in a survey of 21 cultivars. The majority of SSRs were highly polymorphic and diploid and showed simple Mendelian inheritance, although about 25% of markers generated complex banding patterns. Three microsatellite markers were sufficient to differentiate between all 21 cultivars. Gianfranceschi *et al.* (1998) developed 16 SSR markers that amplified all alleles from 19 cultivars, breeding selections and *M. floribunda* 821. Two selected SSRs were able to distinguish all cultivars except 'Starking' and 'Red Delicious'. Hokanson *et al.* (1998) screened accessions from a core subset of the germplasm repository with eight SSRs. The primer pairs differentiated all but seven pairs of accessions.

3.7.8 Molecular maps

The first linkage map of apple was based on a progeny of 56 seedlings from a cross of 'Rome Beauty' × 'White Angel' that com-

bined isozyme, RAPD and restriction-fragment length polymorphism (RFLP) markers (Hemmat *et al.*, 1994). Conner *et al.* (1997) developed maps for 'Wijcik McIntosh' and for two advanced scab-resistant selections from the Cornell breeding programme. Maliepaard *et al.* (1999) reviewed the maps for 'Prima' × 'Fiesta', the first progeny used for mapping apple in Europe. One hundred and fifty-five F₁ seedlings were genotyped with 208 markers, which included RFLPs, RAPDs, isoenzymes and microsatellites. The European DARE programme has as one of its goals the identification of molecular markers linked to genes for resistance. Five molecular maps, mainly involving SSRs and AFLPs, have been constructed. Research is conducted in France, Germany, Italy, Greece, The Netherlands and Switzerland. Mapping populations also include 'Fiesta' × 'Discovery'; 'Fiesta' is susceptible and 'Discovery' has a high level of resistance to both scab and mildew. Researchers at INRA in France are using the cross 'Discovery' × TN10-8. Researchers at the University of Bologna in Italy and in Greece are mapping 'Durello di Forlì' × 'Fiesta', while those in Ahrensberg, Germany, are mapping 'Prima' × 'Discovery'. A common set of AFLPs will be tested in mapping populations that have 'Discovery' as a parent.

3.7.9 Comparative mapping

Mapping of resistance-gene analogues (RGAs) from other species is ongoing. Comparative mapping with other members of the *Rosaceae*, especially with *Pyrus* and *Prunus*, is likely. Several microsatellite repeats in peach (*Prunus persica* (L.) Batsch) were also amplified in apple (Cipriani *et al.*, 1999).

3.7.10 Bacterial artificial chromosome (BAC) library of apple

Vinatzer *et al.* (1998) reported the construction of a BAC library using 'Florina', a scab-resistant cultivar (*V_f* gene). The BAC library

is a prerequisite for the construction of a physical map of apple and for map-based cloning of *V_f* or other apple genes.

3.8 Biotechnology

Name recognition in marketing apples is important. Thus, using biotechnology to change a key characteristic of a popular commercial cultivar and yet maintain varietal identity is very desirable. This objective cannot be achieved in traditional breeding because of the need to use a modified back-cross procedure due to self-incompatibility and inbreeding depression.

3.8.1 Somaclonal variation

There has been an ongoing debate about the effect of tissue culture on apple and the extent of somaclonal variation that might exist. This has important implications for the genetic transformation and regeneration of commercial cultivars. Somaclonal variation for resistance to the fire blight pathogen *E. amylovora* and for alterations to rooting ability and shoot proliferation *in vitro* was examined by Donovan *et al.* (1994a,b). Zimmerman (1997) reported that micropropagated trees of 'Redspur Delicious' exhibited tree-to-tree variation and that most replicates did not maintain the spur habit. However, micropropagating spur-type trees from previously micropropagated trees that did retain the spur habit was successful in having spur habit maintained. When tissue culture-derived 'Gala' and 'Royal Gala' clones that were obtained via axillary and adventitious bud formation were compared with conventionally grafted trees by McMeans *et al.* (1998), very little somaclonal variation was observed in morphological or reproductive traits (Plate 3.5). Yet Zimmerman and Steffens (1995) reported that tissue-cultured 'Gala' trees often developed burr knots 6–7 years after being transferred to the field. They suggested that tissue cultures should be re-established annually to prevent this problem.

3.8.2 Regeneration and transformation

The literature in this area is extensive. The reader is referred to several reviews as a starting-point, but advances are continually being made. Protoplast fusion (symmetric and asymmetric) has been tested in apple and some tentative somatic hybrids have been identified (Huancaruna Perales *et al.*, 2000). Singh and Sansavini (1998) reviewed transformation across fruit crops, while Hammerschlag (2000) reviewed transformation of *Malus*. De Bondt *et al.* (1994, 1996) reviewed factors influencing gene-transfer efficiency during early transformation steps and factors affecting regeneration of transformants. Maximova *et al.* (1998) investigated transformation using green fluorescent protein and found that high transient expression and low stable transformation suggested that factors other than (T)-DNA transfer were rate-limiting.

3.8.3 Transgenes introduced

The first report of transformation of apple occurred in 1989 (James *et al.*, 1989). Trifonova *et al.* (1994) transformed 'Granny Smith' with *nptII* and *ipt* genes, encoding for one of the first enzymes in the cytokinin biosynthetic pathway (Fig. 3.1). In 1995, Yao *et al.* introduced the acetolactate synthase gene into 'Royal Gala' to increase resistance

to the herbicide GleanTM in transgenic plants. James *et al.* (1996) documented the stable expression and Mendelian segregation of the marker transgenes nopaline synthase (*nos*) and the cotransferred gene neomycin phosphotransferase (*nptII*) in the flesh of apple fruits 7 years after the initial transformation. In 1996, 'Gala', 'Golden Delicious' and 'Elstar' were transformed (Puite and Schaart, 1996), followed by 'Delicious' and 'Pink Lady[®]' (Srisikandarajah and Goodwin, 1998) and 'Delicious', 'Greensleeves' and 'Royal Gala' (Maximova *et al.*, 1998).

Bolar *et al.* (1999) developed an efficient transformation system for 'Marshall McIntosh'. Expression of endochitinase from *Trichoderma harzianum* in apple increased resistance to scab and reduced vigour in transgenic 'Marshall McIntosh' (Bolar *et al.*, 2000). There was a significant negative correlation between the level of endochitinase production and both the amount of disease and plant growth.

Yao *et al.* (1999a) grew transgenic 'Royal Gala' apple trees under controlled greenhouse conditions and 20% of the trees flowered in the second year, but, when scion wood from the top of these clones was grafted on to M.9, 85% produced flowers and fruit the next year. Inheritance of three transgenes, *uidA*, neomycin phototransferase II and acetolactate, fit a 1 : 1 ratio in most lines, but in one progeny line the T-DNA integration pattern was complex.



Fig. 3.1. Machine used to transform apple tissue by inserting genes

Two of four transgenic lines possessing the kanamycin resistance gene and antisense polyphenol oxidase (PPO) DNA showed repressed PPO activity and a lower browning potential than control shoots (Murata *et al.*, 2000). Broothaerts *et al.* (2000b) developed a spectrophotometric assay for the analysis of PPO in apple and tobacco leaves to increase efficiency in screening large numbers of transgenic plants (Fig. 3.2).

Transformation of 'Jonagold' with antimicrobial peptide genes (A1-AMP) resulted in 28 independent transgenic lines, which are being tested for resistance to apple scab using artificial inoculation assays (Broothaerts *et al.*, 2000a). At the Apple Research Centre in Morioka, Japan, 'Orin' and the Japanese rootstock 'JM 7' have been transformed with genes encoding the sorbitol-metabolizing enzyme sorbitol-6-phosphate dehydrogenase isolated from apple, chitinase isolated from rice, glucanase from soybean and sacrotoxin from the flesh fly (Soejima *et al.*, 2000).

3.8.4 Rootstocks transformed

Apple rootstocks are also a focus in biotechnology, with M.26 rootstock (Lambert and Tepfer, 1992; Maheswaran *et al.*, 1992; Holefors *et al.*, 1998) and M.7 rootstock transformed (Norelli *et al.*, 1999). M.26 was also transformed with *rolA* and *rolB* (Zhu and Welandar, 2000). Zhu *et al.* (2001) transformed M.9 rootstock with *rolB* and found that in *in vitro* rooting tests all transgenic

clones rooted (83–100%) on hormone-free rooting medium versus 1% for the controls. Root length and root morphology did not differ between transgenic clones and the untransformed controls.

3.8.5 Transgene silencing

Ko *et al.* (1998) found that there were alterations in *nptII* and *gus* expression following micropropagation of transgenic M.7 apple rootstock lines. The *gus* gene was present in non-staining lines. *Gus* gene silencing was due to methylation in some cases, but in others the mixed staining might be due to a mixture of transformed and non-transformed cells.

3.8.6 Challenges

At present, traits that are complex (e.g. yield and flavour) are not likely candidates for improvement by biotechnology. Additionally, there is a need for genes from *Malus* to be cloned, since public concern about transgene technology does differentiate between native and non-native genes. There is also a need for specific promoters, wound-inducible or fruit- or leaf-specific, so that gene expression may be targeted only to the parts of the plant necessary for the desired effect (Gittins *et al.*, 2000). Transgenic testing must ensure that there are no non-target effects and that transgenic lines are stable and non-chimeric.

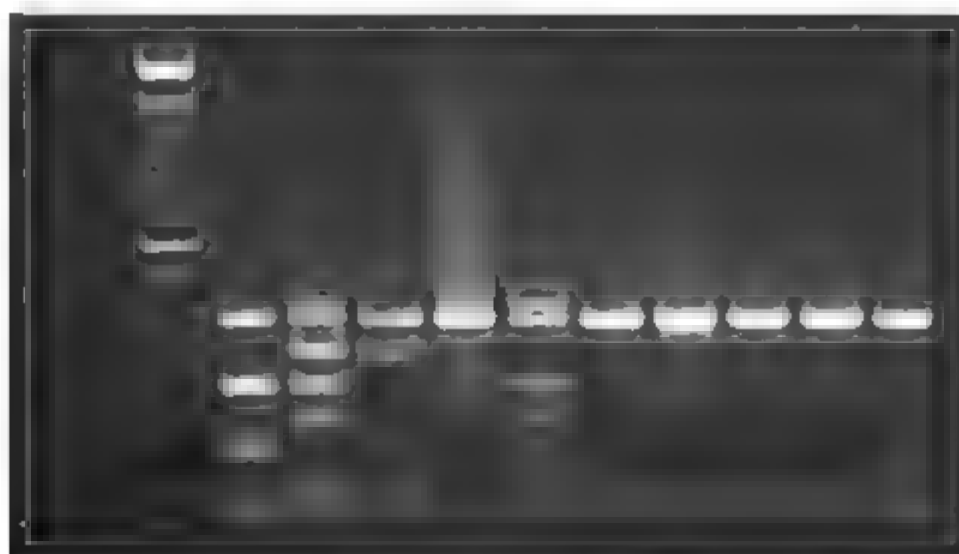


Fig. 3.2. Gel comparing banding patterns of seedlings segregation for disease resistance.

3.9 Future Prospects

3.9.1 *Malus* genes being investigated

As researchers use sequence-information comparisons with *Arabidopsis* mutants and other well-characterized plants, genes from *Malus* are being identified and cloned (<http://www.ncbi.nlm.nih.gov/>). Research on MADS in apple is an example of how initial findings may evolve. In 1997, a MADS-box cDNA clone of the 'Fuji' apple was cloned and characterized (Sung and An, 1997). Yao *et al.* (1999b) found that MADS-box genes were expressed in different parts of the fruit. Parthenocarpic apple fruit production was then found to be conferred by transposon insertion mutations in a MADS-box transcription factor (Yao *et al.*, 2001).

3.9.2 1-Aminocyclopropane-1-carboxylate (ACC) synthase and ACC oxidase

In 1991, Dong *et al.* cloned a cDNA encoding ACC synthase, the main gene responsible for ethylene production during ripening. In 1998, genomic clones associated with ACC oxidase and polygalacturonase mRNAs in ripe apples were isolated and expression was monitored in three cultivars (Dong *et al.*, 1998). The activity and tissue specificity of the promoters were analysed in transgenic tomato (Atkinson *et al.*, 1998). Harada *et al.* (2000) hypothesized that a low level of ethylene production might be caused by a mutated allele of the ACC synthase gene (Md-ACS1).

3.9.3 Additional genes involved in flowering

Dong *et al.* (1998) constructed a cDNA library from developing fruits of apple, 2 days after pollination. Differential screening for pollination-induced genes resulted in the isolation of MdDAD1, an apple homo-

logue of genes for DAD1 (defender against cell death 1). Southern hybridization indicates that apple contains at least two DAD1 homologues. Transcript levels vary between tissues and are induced by flower pollination and senescence of leaves, petals and fruits. MdDAD1 mRNA was distributed primarily in the vascular bundles. Other research identified apple mRNAs related to bacterial lignostilbene dioxygenase and plant small-auxin-up-RNA (SAUR) genes, which were preferentially expressed in flowers (Watillon *et al.*, 1998). Kotoda *et al.* (2000) examined expression patterns of homologues of floral meristem identity genes *LFY* and *AP1* during flower development in apple. These studies should advance our understanding of floral initiation and development.

3.9.4 Summary

Advances in molecular markers, gene characterization and sequencing and the transformation and expression of transgenes offer great potential to aid the efficiency and effectiveness of genetic improvement in apple. These advances will allow us to manipulate genes affecting quality, disease resistance and plant architecture. Cloning genes from *Malus* will occur with greater frequency and perhaps aid our understanding of the role of transposons in the activation of mutations for colour and plant habit. Transformation using native genes may enhance our knowledge of gene silencing and perhaps gene activation. Adding genes for resistance to apple cultivars with native resistance to disease is likely to impart broader-scale resistance with less likelihood of resistance breakdown. Undoubtedly, new information and new techniques will continue to lead to improvements in fruit quality, storage life, nutrition, resistance to insects and diseases and self-fertility, resulting in new apple cultivars and improvements in existing cultivars.

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4 Characteristics of Important Commercial Apple Cultivars

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4.1 Introduction

The cultivated apple is believed to have originated in central Asia. Its chief ancestor is probably *Malus sieversii*, from the Heavenly Mountains (Tien Shan) on the border of western China, the former USSR and central Asia (Janick *et al.*, 1996). Apples have been cultivated and vegetatively propagated for over two millennia.

Over 10,000 named cultivars exist and breeders worldwide create more new selections annually, but only a few dozen types are widely produced in commerce today

(Janick *et al.*, 1996). The high cost of modern production requires a cultivar to have prolific, consistent yields of uniform, commercial-quality fruit, be amenable to handling, storage and shipping and generate high consumer demand. Resistance to diseases, pests and storage disorders is also important. In the past, most small farms produced their own apples for fresh or preserved use and local markets. Improvements in storage technology eliminated the need for a succession of short-storing apples from early summer to late winter (French, 1970) and displaced some

old, long-keeping apples with less consumer demand, e.g. 'Winesap'. Improved storage and year-round commercial availability also shifted consumption patterns from preserved forms (cider, vinegar, dried apples, apple butter, apple sauce) to fresh apples. Societal changes, including the temperance movement, reduced the demand for cider apples. Apples grown by farm families primarily for cooking, some of which are too acidic for eating fresh, declined as populations became more urban and lifestyles changed. Many older cultivars have specific flaws that prevent commercial production, or their appearance deters a majority of consumers, but they may be fine for home gardens where individual flavour preference and disease/pest resistance are the criteria of prime importance.

French (1970) gives an interesting account of old American cultivars and why they were displaced. Specific faults responsible for the decline of these old cultivars include: lack of market demand or inability to compete with newer cultivars; pronounced biennial bearing; inadequate winter-hardiness; fatal disease susceptibility; narrow adaptation; low yield; lack of precocity; severe preharvest drop; severe water-core; mediocre eating quality; insufficient fruit size; unattractive fruit; poor storage ability.

4.2 Cultivar Descriptions

World production of apples is covered in Chapter 2 of this volume. Here we profile the 12 apples that are currently the most important (by tonnage) in world trade. Tree and fruit descriptions are presented in note form. Selected pest-susceptibility reports are cited, but should be interpreted with caution. Pest resistance is considerably influenced by climate and cultural practices as well as the genetics of the host and pest. Detailed descriptions of the bacteria and fungi (Chapter 18) and insects and arachnids (Chapter 19) mentioned in this chapter are covered elsewhere in this volume.

4.2.1 'Delicious'

'Delicious' arose unwanted in the field of Jesse Hiatt of Peru, Iowa, USA, in about 1872 (Maas, 1970a; Fear and Domoto, 1998). Mr Hiatt cut the tree down twice before allowing it to persist, because it was not growing in the row. The parentage is unknown; a nearby 'Yellow Bellflower' tree may have been the seed parent (Maas, 1970a; Khanizadeh and Cousineau, 1998), or 'Delicious' may have arisen as a sprout from a seed or a seedling rootstock. Mr Hiatt was impressed by the fruit and named the cultivar 'Hawkeye'. It was eventually purchased by Stark Brothers Nursery, who renamed it 'Delicious' and introduced it commercially in 1895. In its various forms, 'Delicious' has become the world's most important and best-studied cultivar. It has long been the backbone of the US industry. With its high colour and distinctive appearance, 'Delicious' is frequently used as a generic apple in advertisements and artwork. 'Delicious' is an important cultivar in the USA (especially Washington), the European Union, Australia, China and many other countries. *Synonyms*: 'Hawkeye', 'Red Delicious', 'Stark Delicious'.

4.2.1.1 Tree

Standard trees moderately vigorous, upright-spreading, spurring fairly freely, basitonic, Lespinasse type II. Medium in precocity, productivity and regularity of bearing. Widely adaptable, but performs best in areas with warm summers, high light intensity and adequate water-supply. Bears primarily on spurs. Much of modern production is on spur-type trees, i.e. trees with a high proportion of the laterals being spurs instead of long shoots (classic type I in the Lespinasse system). Spur types tend to be more upright and require limb spreaders. They are usually more precocious than standard strains and a little smaller in final tree size. Diploid, not self-fertile; blooms mid-season. Moderately to very cold-hardy (Maas, 1970a; Kabluchko and Grigorenko, 1976; Khanizadeh and Cousineau, 1998); hardy to US Department of Agriculture

(USDA) zone 4b (-34°C) (Strang and Stushnoff, 1975; Luby *et al.*, 1999). King blooms more sensitive to frost than those of 'McIntosh' or 'Golden Delicious', similar to 'Jonagold', and less sensitive than 'Fuji' (Marro and Deveronico, 1979; Shibata and Mizuno, 1988; Mittelstadt, 1989; Mittelstadt and Salzer, 1989). Chilling requirement medium to high, about 600–800 h in some estimations (Semadi, 1988) and 1200–1300 units in others (Ghariani and Stebbins, 1994). Resistant to heat, drought and hail (Khalin, 1971; Timoshenko, 1976; Khalin and Dzetsin, 1980). Not prone to preharvest drop.

4.2.1.2 Fruit

See Bultitude (1983). Harvested at 140–160 days after full bloom (DAFB) (Smock and Neubert, 1950; Maas, 1970a; Khanizadeh and Cousineau, 1998) in a single pick. Maturity indices include DAFB, ground colour change from green towards yellow, flesh colour change from green to cream, starch index and soluble solids. Size medium to large; adequate thinning important for fruit size and return bloom. Shape oblong conic to truncate conic, sometimes waisted below apex; prominently ribbed and irregular with very pronounced crowning at apex (Plate 4.1). Stem cavity wide and fairly deep, usually russet-free. Stems medium, stout, sometimes fleshy, exserted. Calyx basin wide and deep, distinctly ribbed; eye medium, a little open. Skin very tough, resistant to bruising, russet-free, dry, smooth and glossy. Ground colour greenish yellow, overcolour varies with strain; original said to be strawberry red with darker stripes (Maas, 1970a); newer strains can be close to 100% dark crimson. Flesh cream, sometimes tinged with green, very firm, fine-grained, juicy, mealy if overripe. Flavour sweet, low in acid, aromatic, distinctive.

USES Very good for dessert, fair to poor for culinary uses, fair for sauce, good for juice, fair to poor for drying, good for minimally processed slices (Smock and Neubert, 1950; Kim *et al.*, 1993b; Root, 1996; Lisowa *et al.*, 1997). Exceptionally good for handling and shipping.

4.2.1.3 Storage and postharvest

'Delicious' stores 3–4 months in air (Smock and Neubert, 1950). Optimal controlled-atmosphere (CA) storage recommendations vary with region, ranging from 0.7 to 2.5% O_2 , 0 to 4.5% CO_2 , -0.5 to 1.1°C , for storage of 6–11 months (Kupferman, 1997). 'Delicious' is not chilling-sensitive or sensitive to low O_2 . It is prone to scald, particularly if picked too early (125–135 DAFB). Spur types should be picked 7–10 days later than standard strains for comparable scald control (Fisher and Ketchie, 1989). The lobes are sensitive to heat injury and can develop symptoms resembling scald (Meheriuk and McPhee, 1984).

'Delicious' is also susceptible to water-core, especially as maturity advances. Later-harvested fruit can also become mealy in storage. 'Delicious' can get bitter pit, but it is preventable by proper fertilization practices and crop-load management. It is susceptible to mouldy core.

4.2.1.4 Production notes

'Delicious' is susceptible to apple scab, resistant to powdery mildew and highly resistant to fire blight. It is resistant or slightly susceptible to cedar-apple rust, and susceptible to quince rust and hawthorn rust (Aldwinckle, 1974; Warner, 1992). 'Delicious' is also moderately susceptible to *Botryosphaeria* canker, very susceptible to *Valsa* canker (Bessho *et al.*, 1994) and susceptible to *Nectria* canker, black-rot canker (Miller, 1973), *Monilinia fructigena* but not *Monilinia laxa* (Massodi and Bhat, 1988; Reznikova, 1990), *Clathridium corticola* fruit rot (Thind *et al.*, 1975), leaf spot (Macek, 1974), *Alternaria* leaf blotch (Saito and Takeda, 1984) and apple scar skin viroid (Desvignes *et al.*, 1998). It is resistant to crown rot (Aldwinckle *et al.*, 1975) and brown leaf spot (Koropatnyuk, 1974) and tolerant of apple mosaic virus (Singh *et al.*, 1981).

'Delicious' is very prone to red-mite infestation (Smock and Neubert, 1950; Fisher and Ketchie, 1989; Khanizadeh and Cousineau, 1998), but is frequently considered tolerant to damage from this pest.

(Beers and Hull, 1987). 'Delicious' is susceptible or very susceptible to mullein bug (*Campylomma verbasci* Meyer) (Thistlewood *et al.*, 1989), *Operophtera brumata* Linnaeus, *Rhopalosiphum insertum* Walker and rosy apple aphid (Cottwald, 1987). It was found to be more resistant than some cultivars to maize weevil (Lorenzato and Grellmann, 1987), tufted apple bud moth (Knight and Hull, 1988), apple rust mite (Bulgak, 1981), two-spotted mite (Yiem, 1993), woolly apple aphid (Asante, 1994) and apple maggot (Goonewardene *et al.*, 1979).

'Delicious' is not very sensitive to sunburn. Problems may occur regionally with internal bark necrosis, bud union necrosis, poor fruit set, variable shape and dead spur disorder (Fisher and Ketchie, 1989; Fear and Domoto, 1998).

4.2.1.5 Breeding

'Delicious' is one of the top five most frequent founding clones of modern apple cultivars, and has been especially used in breeding in the USA and Pacific rim (Noiton and Alspach, 1996). It is a source of resistance to fire blight and powdery mildew and of long storage life. Cultivars with 'Delicious' in their parentage include 'Fuji', 'Gala', 'Empire', 'Melrose', 'Earlidel', 'Sekaiichi', 'Huashuai', 'Jinguang', 'Jupiter', 'Summerdel' and the scab-resistant cultivars 'Priscilla', 'Enterprise', 'Florina' and 'McShay', among others.

4.2.1.6 Sports

Over 100 strains of 'Delicious' exist; the original strain is scarcely grown at present. All strains offer improved colour (timing and/or amount, in stripe or blush patterns) and many are also spur types. Strains vary in many other traits, including productivity, alternate bearing, fruit drop, susceptibility to disorders, fruit shape, maturity time, fruit set, flesh greenness, sugar and acid content, firmness, date of full bloom, winter-hardiness and consumer acceptance. Most strains originated as spontaneous mutations in commercial orchards. The first colour sport was 'Richared Delicious' in

1919. Earlier colouring was important to growers, because the original strain often coloured so late in maturation that the fruit would become mealy in storage. The name 'Starking Delicious' has been given to a succession of superior standard strains by Stark Brothers Nursery, beginning with the colour sport found by L. Mood in 1921. Most spur types have been whole-tree mutations (Fisher and Ketchie, 1989). In the mid-1950s, 'supercolour' sports began to emerge, such as the spur-type 'Starkrimson Delicious' strain found by R. Bisbee in 1951 (Maas, 1970a). Sports include: 'Starking Delicious', 'Starkrimson Delicious', 'Royal Red', 'Morgan Spur[®]', 'Oregon Spur[®] II', 'Midnight[™] Red Spur Delicious', 'Apex', 'Topred[™]', 'Imperial Double Red Delicious', 'Ace[®] Spur Red Delicious', 'Ultrared', 'Silverspur', 'Hardispur Delicious', 'Sturdeespur Delicious', 'Red Zenith[®] Spur', 'Scarlet Spur[®]', 'Redchief[®]', 'Super Chief[®]' and many others.

4.2.2 'Golden Delicious'

'Mullins Yellow Seedling' was a chance seedling found by A.H. Mullins of Clay County, West Virginia, USA. The date of origin is either 1890 (Smith, 1971; Bultitude, 1983) or 1905 (Percival and Proctor, 1994; Baugher and Blizzard, 1998). In 1914, propagation rights were sold to Stark Brothers Nursery, who introduced the cultivar as 'Golden Delicious' (Baugher and Blizzard, 1998). The parentage of 'Golden Delicious' is unknown, but is speculated to be either 'Grimes Golden' open pollinated (Smith, 1971; Bultitude, 1983) or 'Grimes Golden' × 'Golden Reinette' (Maas, 1970b; Khanizadeh and Cousineau, 1998). 'Golden Delicious' is undoubtedly the most important yellow apple in the world, and is second only to 'Delicious' in world production. 'Golden Delicious' is grown very widely, but is especially popular in Europe and the USA. It has, however, lost ground to newer cultivars such as 'Jonagold', 'Elstar', 'Gala' and 'Pink Lady[®]' in some areas.

4.2.2.1 Tree

Moderately vigorous, spreading, spurs very freely, wide branch angles, mesotonic. Very easy to manage, adaptable to a wide range of soil and climatic conditions. Fruit finish and texture best in warm areas with dry summers (Maas, 1970b). Bears on 1-year-old wood, terminals and spurs (type III in the Lespinasse system). Precocious, usually annual-bearing, highly prolific, not subject to preharvest drop. Diploid with abundant pollen, slightly self-fertile (Maas, 1970b; Pasqual *et al.*, 1981; Niu *et al.*, 1994). Blooms mid-season. Usually considered only moderately cold-hardy. Reports disagree on its sensitivity to bloom frost (high: Nybom, 1992; low: Mittelstadt and Koch, 1979; Mittelstadt, 1989), but it appears to be more resistant than 'Delicious'. Chilling requirement reported as 600–800 h (Tabuenca and Jimenez, 1984; Semadi, 1988; Barahona *et al.*, 1992) or 1275 units (Ghariani and Stebbins, 1994). Considered fairly drought-resistant in Turkmenistan (Kosheleva *et al.*, 1986). Flood tolerance intermediate, less than 'Jonathan' (Lee *et al.*, 1983).

4.2.2.2 Fruit

See Smith (1971), Bultitude (1983), Khanizadeh and Cousineau (1998). Harvested 135–150 DAFB (Smock and Neubert, 1950; Maas, 1970b; Khanizadeh and Cousineau, 1998), usually in a single pick, when the ground colour starts to change from green to yellow (sometimes earlier for CA storage). Size medium to large; round-conic to oblong, ribbed on body and distinctly five-crowned at apex (Plate 4.2). Stem cavity deep and rather narrow, with some russet. Stems long, slender, well exerted. Calyx basin medium in depth and width, ribbed, sometimes partly russeted. Eye closed or partly open. Skin dry, tender, thin, smooth and prone to russet in certain climates, especially if humid. Russet-resistant sports and gibberellins $A_4 + A_7$ (GA_{4+7}) sprays sometimes used commercially to reduce skin russet. Ground colour dull greenish yellow, becoming golden yellow, sometimes with a slight orange flush but no

stripes. Lenticels conspicuous, fairly large, grey-brown dots, prone to russet. Flesh cream, firm, crisp, tender, fine-grained, juicy. Flavour sweet, a little acid, aromatic. Oxidation of cut flesh is fairly slow (Root, 1996; Khanizadeh and Cousineau, 1998).

USES Very good for dessert and culinary use. Maintenance of flesh integrity makes it suitable for slices (Root, 1996), including minimally processed slices (Kim *et al.*, 1993b). Good for sauce, dehydration and baby food and fair for juice (Maas, 1970b, Root, 1996; Lisowa *et al.*, 1997).

4.2.2.3 Storage and postharvest

'Golden Delicious' stores 3–4 months in air (Smock and Neubert, 1950). Optimal CA conditions vary with region, ranging from 1.0 to 3.0% O_2 , 0 to 4.0% CO_2 , -0.5 to $2.0^\circ C$, for 6–10 months of storage (Kupferman, 1997). 'Golden Delicious' is sensitive to bruising from rough handling or mechanical impact, and bruised fruit is susceptible to storage rots. Fruit is usually waxed to prevent skin shrivelling in storage. Texture becomes mealy if harvested too late (Watada and Abbott, 1985). Susceptibility to scald varies with growing conditions; it can be prevented with diphenylamine (DPA), ethoxyquin or low- O_2 CA storage (Kupferman, 1997). In some areas DPA is not recommended as it causes a blue-grey skin discoloration and 'fixes' chlorophyll in the skin (Lau, 1986). Ultra-ultra-low oxygen (UULO) or pre-treatment with 15% CO_2 prior to CA improves firmness retention at $0^\circ C$ (Watada and Abbott, 1985; Resnizky and Sive, 1991).

4.2.2.4 Production notes

'Golden Delicious' is very susceptible to apple scab. Susceptibility to powdery mildew appears to vary among regions, with reports of both high and low susceptibility being common. 'Golden Delicious' is susceptible to quince rust and certain races of cedar-apple rust (Aldwinckle, 1974; Chen and Korban, 1987; Warner, 1992). It is usually rated as moderately resistant to fire blight. 'Golden Delicious' is among the few culti-

vars with partial resistance to *Nectria* canker (Grabowski, 1987, 1994; van de Weg, 1989). It is partially resistant to *Alternaria* blotch (more than 'Delicious', less than 'Jonathan') (Sawamura, 1972; Bulajic *et al.*, 1996). It is resistant to *M. laxa* Aderhold & Ruhland Honey (Reznikova, 1990) and partially resistant to *Pezizula malicortis* H. Jacks. Nannf. and silver leaf (Borecki and Czynczyk, 1985) and to black-rot canker (Miller, 1973). It is more resistant than 'Delicious' to *Botryosphaeria* canker (Latorre and Toledo, 1984). 'Golden Delicious' is susceptible to fruit rot by *Phytophthora cactorum* (Lebert. & Cohn) Schroter (Mourichon and Salle, 1981; Grove, 1993); it is susceptible to leaf blotch (Janick *et al.*, 1996) and *Phoma* leaf spot (Macek, 1974). 'Golden Delicious' is moderately susceptible to apple mosaic virus and apple witches'-broom mycoplasma-like organism (Kegler *et al.*, 1992) and tolerant of apple scar skin viroid (Desvignes *et al.*, 1998).

'Golden Delicious' is preferred over 'Cox's Orange Pippin' by egg-laying codling moths (Blago and Dickler, 1990) and less preferred than 'Stayman' or 'Rome Beauty' by feeding larvae of tufted apple-bud moth (Knight and Hull, 1988; Meagher and Hull, 1991). It is susceptible to apple fruit moth in India (*Argyresthia conjugella* Zeller) (Khajuria *et al.*, 1987), susceptible to red mite (Kolbe, 1972; Skorupska, 1992), more resistant than 'Fuji' or 'Delicious' to two-spotted mite (Yiem, 1993; Yiem *et al.*, 1993), less resistant than 'Delicious' to apple maggot (Goonewardene *et al.*, 1979) and highly susceptible to rosy apple aphid (Graf *et al.*, 1992).

'Golden Delicious' can develop bitter pit or sunburn under appropriate conditions, but is not considered highly prone to these disorders. Calyx green-end disorder, a flattening and distortion of the calyx end with persistent green colour of the skin, appears to be a result of fluoride toxicity (Seeley, 1979; Barritt and Kammereck, 1983).

4.2.2.5 Breeding

'Golden Delicious' has been used extensively in breeding, especially in the Pacific rim, USA and western Europe. It is valued as a source

for high fruit quality, precocity and good tree habit. In Germany, 'Golden Delicious' progeny were noted as having a high percentage of seedlings with good resistance to fire blight (Fischer *et al.*, 1996). 'Golden Delicious' is one of the top five most frequent founding clones of modern apple cultivars (Noiton and Alspach, 1996). Its progeny are poised to dominate world production in this century (Percival and Proctor, 1994). Apples with 'Golden Delicious' in their parentage include 'Mutsu' ('Crispin'), 'Jonagold', 'Elstar', 'Gala', 'Pink Lady'® ('Cripp's Pink'), 'Sundowner'®, 'Corail'/'Pinova'™, 'Arlet' ('Swiss Gourmet'®), 'Delblush' ('Tentation'®), 'Delcorf' ('Delbarestivale'®), 'Creston', 'Summerred', 'Fu Shuai', 'Sekaiichi', 'Shizuka', 'Pirella', 'Kinsei', 'Sweet Caroline', 'Falstaff', 'Xinguan', 'Tsugaru', 'Shamrock', 'Orin', 'Maigold', 'Delbard Jubilé' and the scab-resistant (V) cultivars 'Sir Prize', 'GoldRush', 'Primiera', 'Ariwa'®, 'Florina', 'Princesa', 'Enterprise', 'Baujade', 'Freedom'®, 'Priam' and 'Prima'.

4.2.2.6 Sports

Numerous strains exist, varying in russet resistance, spurriness, blush, fruit size, earliness of bearing, tree size, yield efficiency, productivity, alternate bearing and powdery-mildew resistance. Götz and Silbereisen (1989) list over 60, including 'Starkspur Golden Delicious', 'Smoothee'® ('Gibson Golden Delicious', 'Golden Glory'™, 'Goldspur'® Delicious'), 'Lutz', 'Lysgolden', 'Belgolden' and 'Reinders'. None exceeds standard 'Golden Delicious' in acceptance (Percival and Proctor, 1994).

4.2.3 'Fuji'

'Fuji' is the offspring of a 'Ralls Janet' × 'Delicious' cross made in 1939 (Smith, 1971, Kikuchi *et al.*, 1997). It was named 'Fuji' in 1962 by the Horticulture Research Station in Morioka, Japan. The name commemorates Fujisaki in Aomori, Japan, where the cross was made (Yoshida *et al.*, 1998). 'Fuji' is the most important apple in Japan and China and is a major cultivar in Korea,

Brazil, Argentina, Chile and Australia. It has been planted extensively in both hemispheres in the past decade. About 80% of current 'Fuji' acreage is located in China (Avermaete, 1999). 'Fuji' has a long storage and shelf life, perhaps because of its low ethylene production and low respiration rate (Yoshida *et al.*, 1998).

4.2.3.1 Tree

Vigorous, spreading and willowy, mesotonic, precocious, productive but somewhat slow to spur in initial years (Tustin, 1994) and produces some blind wood. Tip bearer (Lespinasse type IV), with long darts; flowers on 1- and 2-year-old wood. Difficult to thin chemically, strong tendency to bear biennially. No preharvest drop. Diploid, requires a pollinizer, blooms in mid-season. Flooding tolerance intermediate (Lee *et al.*, 1983). Trees winter-hardy but with a lower chilling requirement than 'McIntosh' or 'Delicious' (Ghariani and Stebbins, 1994), estimations of chilling requirement vary from 600–800 h (Barahona *et al.*, 1992) to 1050 units (Ghariani and Stebbins, 1994). More sensitive to bloom frost than 'Delicious' or 'Jonagold' (Shibata and Mizuno, 1988).

4.2.3.2 Fruit

Harvested 140–180 DAFB, early to mid-November in Japan. May require several picks, depending on colour management. Ground colour, overcolour and starch disappearance are used as maturity indices, but not firmness or soluble solids (Argenta *et al.*, 1995; Britz, 1998; Yoshida *et al.*, 1998). Size large; shape round-conic to round-oblate, ribbed on body (Plate 4.3). Stem cavity wide and moderately shallow, sometimes partly lined with brown russet. Stems long, stout, well exerted. Calyx basin wide, moderately deep, distinctly ribbed. Eye medium, closed, anthers frequently persisting. Lenticels large conspicuous white dots. Skin tough, smooth, dull or sometimes roughened with russet. Susceptible to stem punctures (Britz, 1998). Ground colour pale yellow-green with red blush and darker stripes (Smith, 1971). Colour frequently poor on standard strain

without special management. Elaborate practices to boost colour development have been developed in Japan, including bagging (Arakawa, 1998), leaf removal, reflective mulches and fruit turning. Flesh cream, above average in crispness, firmness, juiciness, fine-grained. Flavour sweet and very mild, high in sugar and low in acidity. Low in dietary fibre compared with other cultivars (Gheys *et al.*, 1997).

USES Excellent for dessert, good for processing quality, except cider (Yiem *et al.*, 1980).

4.2.3.3 Storage and postharvest

'Fuji' is highly prone to water-core, prone to stem-end cracking, bitter pit, cork spot and external brown staining. Severe water-core shortens storage life and may cause internal breakdown. Compared with other cultivars, 'Fuji' has a very slow rate of firmness loss and a long shelf life (Yoshida *et al.*, 1998). For short-term storage, CA is no better than regular atmosphere storage for firmness retention, but CA improves retention of acidity (Drake, 1993). 'Fuji' is susceptible to internal browning in long-term CA (≥ 6 months); the problem is worse with mature fruit. Short-term (3 days) exposure of fruit samples at harvest to 20 kPa CO₂ may be useful as a predictor of susceptibility to internal browning (Volz *et al.*, 1998). 'Fuji' is also susceptible to core browning, a disorder whose incidence rises with later picking and preharvest calcium treatments (Yoshida *et al.*, 1998). Early-picked 'Fuji' may develop scald, but it is preventable with DPA, ultra-low oxygen (ULO) or hypobaric storage (Kupferman, 1997; Yoshida *et al.*, 1998). Optimum CA conditions vary with region, ranging from 0.7 to 2.5% O₂, < 0.5 to 2.0% CO₂ at 0–1°C, for 7–11 months of storage (Kupferman, 1997).

4.2.3.4 Production notes

Bloom thinning is recommended, but some chemicals cause russet (Jones *et al.*, 1998; Yoshida *et al.*, 1998). Thinning to singles with 75 leaves per fruit is recommended in Japan (Yoshida *et al.*, 1998).

'Fuji' is highly susceptible to apple scab and fire blight and moderately resistant to powdery mildew. It is resistant to quince rust; cedar-apple rust lesions occurred on leaves but not fruit in one 3-year study (Warner, 1992). 'Fuji' is considered susceptible or highly susceptible to *Alternaria* blotch (but less so than 'Delicious') (Brooks and Olmo, 1997; Khanizadeh and Cousineau, 1998; Yoshida *et al.*, 1998), lenticel infection by apple rot (*Botryosphaeria dothidea* Moug. Fr. Ces & DeNot) (Kim and Kim, 1989), fruit ring rot and twig cankers (*Physalospora piricola* Dose) (Luo *et al.*, 1996), *Valsa* canker (Bessho *et al.*, 1994), bitter rot and *Mucor* rot (*Mucor piriformis* E. Fisch) (Yoshida *et al.*, 1998). It is also sensitive to apple scar skin viroid (Desvignes *et al.*, 1998) and the viruses russet ring and apple fruit crinkle (Yoshida *et al.*, 1998).

'Fuji' is fairly resistant to apple maggot (Lamb *et al.*, 1988) and susceptible to two-spotted spider mite (Yiem, 1993; Yiem *et al.*, 1993). 'Fuji' is very susceptible to fruit skin or lenticel russetting and moderately prone to sunburn (Britz, 1998).

4.2.3.5 Breeding

'Fuji' is valued as a parent for its large fruit, excellent quality and long storage life. It is currently being used in many breeding programmes, especially on the Pacific rim. 'Fuji' offspring include 'Himekami', 'Hokuto', 'Huaguan', 'Huashuai', 'Senshu' and the scab-resistant (V_r) Brazilian cultivar 'Catarina'.

4.2.3.6 Sports

At least 128 named strains occur in Japan alone (Komatsu, 1998). Colour sports are the most common. Strains vary in stability, colour pattern, intensity and amount of colour, ploidy level, spurriness, climatic adaptation, eating quality and harvest time. In Japan, the striped sports are highly favoured, but blush sports may colour better in warm climates (Komatsu, 1998). Other mutants include 'Beni-Shogun', 'Seirin Spur', 'Tensei' (tetraploid), 'Sun FujiTM', 'Myra Red Fuji', 'Jubilee Fuji', 'Yataka' and 'Takano Wase'.

4.2.4 'Granny Smith'

'Granny Smith' is a chance seedling discovered on the farm of Maria Ann and Thomas Smith of Ryde, New South Wales, Australia. The original tree was fruiting by 1868. 'Granny Smith' is believed to be an open-pollinated seedling of 'French Crab', but it also resembles some of the American 'Greening' cultivars and 'Cleopatra' (Warrington, 1998). Although there have been significant plantings of 'Granny Smith' since the 1920s in Australia, it has only become an important apple in world trade since 1950. 'Granny Smith' is chiefly a southern hemisphere apple. It has been grown extensively in Australia, Argentina, Chile, New Zealand and South Africa. Unmet consumer demand stimulated significant planting in western North America and southern Europe in the 1970s. Today 'Granny Smith' accounts for a third of southern hemisphere exports (Avermaete, 1999).

4 2 4 1 Tree

Moderately vigorous, upright-spreading, spurs fairly freely, but has some blind wood (Bultitude, 1983; Khanizadeh and Cousineau, 1998). Precocious, bearing heavy annual crops. Production of 120–130 t ha⁻¹ is routine in New Zealand, but yield is frequently lower elsewhere (Warrington, 1998). In the Lespinasse system, 'Granny Smith' is type IV (acrotonic tip bearer). Fruit are initially borne on branch tips but later also on laterals, primarily 1- and 2-year-old wood. Partially self-fertile, diploid, partially self-thinning (Warrington, 1998). Cold-hardiness moderate, adequate for central Washington State but not Quebec or Minnesota (Khanizadeh and Cousineau, 1998; Luby *et al.*, 1999). Blooms mid- to late season. High resistance to drought and moderate resistance to heat reported from the Ukraine (Khalin, 1989). Chilling requirement reported as 400–600 h in Algeria (less than 'Delicious' or 'Golden Delicious'), 600–800 h in Ecuador, 1040 units in the USA, similar to 'Fuji' or 'Jonagold' (Semadi, 1988; Barahona *et al.*, 1992; Ghariani and Stebbins, 1994).

4.2.4.2 Fruit

Harvested 170–210 DAFB in a single pick (Janick *et al.*, 1996; Khanizadeh and Cousineau, 1998; Warrington, 1998). Size medium to large; shape round to round-conic, fairly regular, slightly flattened at base and apex, slightly five-crowned at apex, uniform (Plate 4.4). Stem cavity fairly narrow and deep, sometimes partly lined with grey russet. Stems moderately long and slender, level with base or exerted. Calyx basin medium in width and depth, distinctly ribbed, puckered and russet-free. Eye is medium, closed or slightly open. Skin thick, tough, resists bruising, smooth, waxy, becoming greasy with maturity, lacks bloom. Ground colour bright green, becoming greenish yellow, with large conspicuous areolar white lenticels. Sometimes a slight pink blush present but no stripes. Flesh greenish white, very firm, rather coarse, juicy, subacid, tart-sweet, refreshing, but lacking in flavour.

USES Good dual-purpose dessert and culinary apple. Fruit especially high in pectin (Blagov, 1998).

4.2.4.3 Storage and postharvest

'Granny Smith' is a long-keeping apple, possibly because of its low ethylene production (Warrington, 1998). It is very susceptible to superficial scald, particularly if picked too early, but this disorder can be controlled with DPA and/or ULO storage. Premium postharvest quality is attained when the fruit is picked with a medium green ground colour and when all starch has disappeared from the core area (Warrington, 1998). Optimal CA conditions range from 0.8 to 2.5% O₂, 0 to 5.0% CO₂, -0.5 to 2°C, for 7–11 months of storage (Kupferman, 1997). Incidences of core flush and scald are higher in warm climates. 'Granny Smith' may develop bitter pit and water-core if picked too late (Khanizadeh and Cousineau, 1998).

4.2.4.4 Production notes

'Granny Smith' is susceptible to scab, moderately to highly susceptible to powdery

mildew and very susceptible to fire blight (Jeger *et al.*, 1986; Khanizadeh and Cousineau, 1998), but is resistant to cedar-apple rust and quince rust (Warner, 1992, Khanizadeh and Cousineau, 1998). It is more resistant than 'Delicious' to *Botryosphaeria* trunk canker (Latorre and Toledo, 1984) and is tolerant of apple scar skin viroid (Desvignes *et al.*, 1998). Compared with 'Delicious' it is more resistant to red mite (Monetti and Fernandez, 1996) but less resistant to woolly apple aphid (Asante, 1994).

4.2.4.5 Breeding

'Granny Smith' is a parent of the French cultivars 'Baujade' (V₉) and 'Delgaly'.

4.2.4.6 Sports

Sports include 'Granspur', 'Greenspur', 'Earlee Grannee'. These strains reportedly differ from the standard in fruit size, flesh colour (whiter), tree spurriness or compactness, ripening time, fruit set, internode length, lenticel prominence, productivity and the presence of dark green stripes in 'Granspur' (Brooks and Olmo, 1997). Most plantings are still standard types. Some believe that spur types have poorer fruit quality (Warrington, 1998).

4.2.5 'Gala'

'Gala' is the product of two generations of controlled crossing by amateur breeder J.H. Kidd of Wairarapa, New Zealand (White, 1998). 'Gala' is the offspring of a cross of 'Kidd's Orange Red' × 'Golden Delicious' made about 1934. 'Kidd's Orange Red' was itself a cross of 'Delicious' × 'Cox's Orange Pippin' (Noiton and Alspach, 1996). The apple was named 'Gala' in 1962, and released for commercial planting in 1965. However, it did not become really popular until the mid-1970s when several red colour sports appeared (Tustin, 1990). 'Gala' is an important cultivar in New Zealand, Brazil, Argentina, Chile, Australia, China, the USA and Europe (especially France), and has been planted extensively in both hemispheres in the past decade. *Synonym*: 'Kidd's D 8'.

4.2.5.1 Tree

Moderately vigorous, upright-spreading, with long pliant branches, heavily spurred, mesotonic habit. Type III in the Lespinasse system, like 'Golden Delicious' but with narrower branch angles. Fruit borne on 1- and 2-year-old wood, terminals and long strong bourse shoots (Tustin, 1990). Highly precocious, bears prolific annual crops. Devigorating burr knots may form at the base of older limbs (Tustin, 1990). Wood is brittle and prone to breakage. Easy to train with modern methods, widely adapted. Fruit size and colour very responsive to light exposure. Cold-hardiness moderate, similar to 'Golden Delicious' (Luby *et al.*, 1999). Chilling requirement estimates vary from 600–800 h (Barahona *et al.*, 1992) in Ecuador to 1150 units in Oregon, USA (Ghariani and Stebbins, 1994). Diploid, somewhat self-fertile. Extended bloom, starting mid-season. Fruit set heavy; easy to thin chemically and not prone to biennial bearing. Fruit quality best on 2-year-old spurs; renewal pruning is recommended (Tustin, 1990).

4.2.5.2 Fruit

See Smith (1971), Bultitude (1983), Khanizadeh and Cousineau (1998). Harvested 120–140 DAFB, 2–4 weeks before 'Delicious'. Fruit adhere well to tree and can be hard to pick; preharvest drop minimal. Cull percentage typically low. Ripening uneven; requires at least three picks, based on ground colour change from green to creamy yellow. Size small to medium and usually uniform; shape round-conic to oblong-conic or oblong, with ribbing on body; distinctly five-crowned at apex (Plate 4.5). Stem cavity medium in width, deep to very deep, partly lined with grey russet. Prone to stem-end russet in some climates. Stems long and slender, exerted. Calyx basin medium, eye closed or a little open. Skin russet-free, smooth and glossy, becoming greasy; not susceptible to bruising; occasionally some scarf skin at base. Develops stem-end cracking when fully to overmature. Ground colour creamy yellow to golden yellow, partly to fully flushed and flecked with

bright orange-red and strewn with deeper red stripes. Lenticels fairly inconspicuous. Flesh pale yellow, juicy, firm, crisp, fine-grained. Flavour sweet, low in acid, refreshing, aromatic, excellent quality.

USES Main use is dessert. Suitable for drying (Lisowa *et al.*, 1997).

4.2.5.3 Storage and postharvest

'Gala' has no significant storage disorders but only a medium-term storage life (Tustin, 1990). CA recommendations vary with region and strain; optimum conditions range from 1 to 3% O₂, < 0.5 to 2% CO₂, 0 to 3°C for storage of 4–9 months (Kupferman, 1997).

4.2.5.4 Production notes

'Gala' is highly susceptible to apple scab (especially on fruit) and fire blight, susceptible to *Nectria* canker and silver leaf and moderately susceptible to powdery mildew. It is moderately susceptible to cedar-apple rust and resistant to quince rust (Warner, 1992). It is highly resistant to *Alternaria* blotch (Shin *et al.*, 1986) and resistant to *Botryosphaeria berengeriana* deNot stem canker and fruit rot (Melzer and Berton, 1986). It is susceptible to russet ring virus, apple mosaic virus (Brooks and Olmo, 1997; Khanizadeh and Cousineau, 1998) and apple scar skin viroid (Desvignes *et al.*, 1998). 'Gala' is fairly resistant to maize weevil in Brazil (Lorenzato and Grellmann, 1987).

4.2.5.5 Breeding

'Gala' is in current use in many breeding programmes throughout the world. 'Gala' offspring include 'Sansa', 'Chinook', 'Pacific Rose', 'Scifresh', 'Pacific Beauty', 'Pacific Queen' and the scab-resistant (*V_f*) French cultivar 'Initial'. Many programmes have other 'Gala' offspring under test.

4.2.5.6 Sports

'Gala' is prone to producing red colour sports, which vary considerably in stability. Both striped and blush sports exist; the tradi-

tional retail market is based on striped types. Strains include 'Tenroy' ('Royal Gala[®]'), 'Imperial GalaTM' ('Mondial Gala[®]'), 'Mitchgla[®]'), 'Regal Gala', 'Galaxy GalaTM', 'Scarlet Gala', 'Fulford GalaTM', 'Brookfield[®] Gala', 'Buckeye[®] Gala', 'Pacific[®] Gala', 'Gale GalaTM', 'Delaf Gala', 'Regal Prince' ('Gala Must[®]') and 'Waliser' ('CrimsonTM Gala'). Strains vary slightly in flower density, maturity date, yield, fruit size and bruise susceptibility in some trials. Usually internal quality does not vary (Kappel *et al.*, 1992; Greene and Autio, 1993).

4.2.6 'Jonathan'

'Jonathan' is believed to be a seedling of 'Esopus Spitzenburg' (or 'Spitzenberg'). In 1826, it was described by Judge Buel of Albany, New York State, USA, who named it after Jonathan Hasbrouck, the man who drew his attention to the tree on the farm of Philip Rick in Ulster County, New York State. 'Jonathan' is still an important cultivar in the USA (Michigan), several eastern European countries and Japan. In western Europe, it has been superseded by more recent cultivars, such as 'Jonagold', but plantings are still present in Switzerland, Korea, Austria, Italy, Germany, New Zealand and Australia. Several good descriptions of 'Jonathan' are available, e.g. Baldini and Sansavini (1967), Nilsson (1987), Sanders (1988), Götz and Silbereisen (1989), Friedrich and Petzold (1993), Morgan and Richards (1993), Manhart (1995), Khanizadeh and Cousineau (1998) and Rom (1998). *Synonyms*: 'New (Esopus) Spitzenberg', 'Philip(p) Rick', 'Ulster (Seedling)', 'Johnathan', 'King Philip(p)', 'Pomme Jonathan', 'Djonathan', 'Dzhonatan'.

4 2 6 1 Tree

Moderately vigorous to rather weak, good central leader, rather dense, feathered, spreading to weeping; wood twiggy, rather thin. Precocious, regular bearing, fairly good productivity. Bears on 2- and 1-year-old wood and somewhat on spurs, type III in the Lespinasse system. Leaves greyish green,

very downy. Blooms late mid-season, fertile pollen, diploid, slightly self-fertile. Slight to medium susceptibility to bloom frost; tree moderately winter-hardy. Suitable pollinizers are listed in Kemp (1996)

4 2 6 2 Fruit

Harvested 140–150 DAFB in multiple picks, picks easily, no preharvest drop. Difficult to get good fruit size (Rom, 1998). Suitable for warm climates; in cooler areas, poorer eating quality (less aromatic). However, fruit from cooler sites stores better. Moderately crisp, quite juicy, sweet, refreshingly subacid to tart, but, on unsuitable sites, a woody metallic taste can occur. Flesh fairly firm, fine-textured, white, slightly green to yellow, with weak, characteristic aroma. Only moderately tasty. Attractive, bright (sometimes pale or brownish), solid crimson-red blush, with some short, broken red stripes, on a yellow-green ground. Skin with finely netted, sometimes patchy russet; slightly waxy, smooth, dry, lustrous with slight bloom and skin hammering; conspicuous, tiny lenticels. Size medium to rather small, shape oblong to round-conical, usually regular and symmetrical; fruit slightly ribbed, mainly at apex and in basin (Plate 4 6). Can be flat-sided. Basin quite narrow, deep, often puckered, with quite small, closed eye; usually russet-free. Stem cavity fairly narrow, deep, usually with some russetting, sometimes streaking over shoulder. Stalk rather slender, short to long. Skin thin to moderately thick, tough, hard, chewy

USES Suitable for processing, cider, dessert, sauce, juice and pies. Shelf life very good to good.

4 2 6 3 Storage and postharvest

'Jonathan' stores for 5 months in air, starting at 3–4°C, later 0–1°C, or for 6 months in ULO or in CA at 0–1°C, 1.5% CO₂ and 1.5–3% O₂ (Kupferman, 1997). Storage above 2–3°C prevents Jonathan spot, in which small black areas surrounding the lenticels expand and sometimes become infected by secondary rots. CA storage prevents

Jonathan spot almost completely; in cold storage, spot can be severe, especially with ripe fruit. The onset of Jonathan spot is delayed by rapid cooling in CA with high CO₂, but excess CO₂ and low O₂ damage fruit. Storage in ULO, 1.5% O₂ and 1.0% CO₂ reduces brown core. Large fruit are prone to decay. Fruit with water-core are not suitable for CA. 'Jonathan' is susceptible to scald, bruising, water-core, internal browning, Jonathan spot; it has medium susceptibility to bitter pit, cork spot and low-temperature browning (LTB). No shrivelling. The risk of internal browning and spot increases with long storage. Jonathan breakdown (under the skin) and senescent breakdown (from core) can occur.

4.2.6.4 Production notes

Deep, light soils are suitable. Night frosts on fruit just before harvest cause internal browning. Colour is often poor on standard 'Jonathan'. Summer pruning can improve fruit colour. Repeated selective picking can reduce storage problems. Incidence of Jonathan spot and internal browning increases with late picking and larger fruit size. Timely picking is necessary for good internal storage quality. 'Jonathan' can produce parthenocarpic fruit after GA application (Thomas, 1963). Early thinning is required; it has a slight tendency to biennial bearing. If trees are biennial or too vigorous, root pruning in combination with supplemental irrigation is a useful tool (Ferree, 1992). Ethephon, naphthaleneacetic acid (NAA) and carbaryl are effective thinning agents (Windle and van Dam, 1989). Calcium sprays, dips or infiltration can reduce bitter pit, cork spot, breakdown (Dewey *et al.*, 1982, Fukuda, 1984) and *Alternaria* rot (Byun and Chang, 1991).

'Jonathan' is very susceptible to mildew (Janse *et al.*, 1998), slightly to moderately susceptible to scab (Rati *et al.*, 1994) and susceptible to cedar-apple rust (Joung *et al.*, 1987), fire blight and bitter rot (Rom, 1998); it is resistant to *Alternaria* leaf spot and has strikingly low susceptibility to *Nectria* canker (Groenwold *et al.*, 1994).

4.2.6.5 Breeding

'Jonagold' is probably the best-known offspring of 'Jonathan', but many other cultivars are descended from it, including 'Idared', 'Jonadel', 'Melrose', 'Megumi', 'Monroe', 'Jonalicious', 'Akane', 'Undine', 'Herma', 'Eva', 'Bonza', 'Rubinovie Duki', 'Malling Kent', 'Blushing Golden', 'Goldjon', 'Cadel', 'Cacanska Pozna' and 'Septer'. See also Smith (1971) and Rom (1988). 'Fiesta' ('Red Pippin®') and 'Elise' ('Roblos®') are both F₂ offspring. It has also been used as a parent in the Ukraine. 'Jonathan' is one of the top five most frequent founding clones of modern apples (Noiton and Alspach, 1996).

4.2.6.6 Sports

A number of sports have been identified, mainly for colour. Examples: 'Anderson Jonathan', 'Kap(p)ai Red Jonathan', 'Jonared', 'Blackjon' ('Red Jonathan'), 'Rode Jonathan Fleuren', 'Rode Jonathan Heines', 'Watson Jonathan', 'Ruby Jon®', 'Jonnee'. Some tetraploids and some irradiated, spur-type mutants are known (Götz and Silbereisen, 1989).

4.2.7 'Jonagold'

'Jonagold' resulted from a 'Golden Delicious' × 'Jonathan' cross made in 1943 at the New York State Agricultural Experiment Station breeding programme in Geneva, New York State, USA, and was introduced in 1968. It was named after its parents. 'Jonagold' is highly appreciated by consumers for its eating quality. It has found special favour in Belgium, where it accounts for ~60% of production (Lambrechts, 1994). 'Jonagold' is also an important cultivar in The Netherlands, Germany, France, Switzerland, Italy, the UK, Japan, Australia, China, the USA and Canada (Way and Brown, 1998).

4.2.7.1 Tree

Vigorous, spreading, large, with good branch angles and spurring freely. Type II in

the Lespinasse system, bears mainly on spurs. Precocious, high-yielding, little pre-harvest drop (Way and Brown, 1998). Bears annually in most districts, but can be biennial. Triploid; requires a pollinizer but cannot donate pollen. Only moderately cold-hardy, has suffered greatly in severe winters in Europe. Blossoms less sensitive to bloom frost than 'Fuji', similar to 'Delicious', and more sensitive than 'Golden Delicious', 'McIntosh' or 'Spartan' (Shibata and Mizuno, 1988; Mittelstadt, 1989; Mittelstadt and Salzer, 1989). Blooms in mid-season with 'Golden Delicious'. Chilling requirement fairly high, ~1100 units (Ghariani and Stebbins, 1994). 'Jonagold' performs best in cooler districts, such as northern Europe. In hot areas, it suffers from sunburn, soft flesh and poor colour.

4.2.7.2 Fruit

See Bultitude (1983), Gotz and Silbereisen (1989), Khanizadeh and Cousineau (1998), Way and Brown (1998). Harvested 140–160 DAFB (Khanizadeh and Cousineau, 1998) and requires three to four picks. Picking date in New York State is just after 'Delicious' (Way and Brown, 1998); earlier in some other localities, with 'Golden Delicious'. Fruit large; round to round-conic with very slight ribbing, moderately flattened and slightly five-crowned at apex (Plate 4.7). Stem cavity wide and fairly deep, lined with grey russet. Stems fairly long and moderately stout, exerted and often curved to one side. Calyx basin fairly wide and quite deep, somewhat ribbed. Eye small, a little open. Skin smooth, prone to scarf skin and frost blemishes, not prone to russet, becoming greasy with maturity. Some susceptibility to bruising. Ground colour is bright yellow tinged with green, with short, broad, broken, dull red stripes over 30–80% of the surface. Lenticels small, grey and green. Flesh light yellow, semi-firm, medium-grained, crisp, very juicy, slow to brown after cutting. The flavour is subacid to sweet, aromatic, very rich.

USES Very good for dessert, culinary use and processing (sauce, slices).

4.2.7.3 Storage and postharvest

When picked at the optimum maturity, 'Jonagold' reportedly stores for up to 6 months in air at -0.5°C (Way and Brown, 1998); otherwise, it becomes soft and bland in long-term air storage. Commercial growers may apply calcium three or more times to improve storage life and prevent bitter pit. Maturity indices for long storage are given by Lau (1992). Optimum CA conditions vary among regions, ranging from 1.0 to 2.5% O_2 , 1.0 to 4.5% CO_2 at $0\text{--}3^{\circ}\text{C}$, for 5–10 months of storage (Kupferman, 1997).

4.2.7.4 Production notes

'Jonagold' is susceptible to scab, fire blight and cedar-apple and quince rusts and highly susceptible to powdery mildew. It is susceptible to *Nectria* canker, but less so than 'McIntosh' or 'Gloster' (Grabowski, 1994). In Korea it is considered highly resistant to *Alternaria* blotch (Shin *et al.*, 1986). In certain regions, it is subject to winter injury, sunburn, bitter pit, alternate bearing or excessive size. Fruit colour can be poor, especially with high crop load or strong vegetative growth.

4.2.7.5 Breeding

'Jonagold' is triploid and cannot be used in conventional breeding

4.2.7.6 Sports

Around 100 strains of 'Jonagold' exist (Goddrie, 1996), including 'Jonagored' (Morren[®]), 'Schneica (Jonica[®])', 'Jored' ('King Jonagold'), 'Jonaveld' (First Red[®]), 'Nicobel Jonagold', 'Rubinstar[®] Jonagold', 'Decosta Jonagold', 'Jonagold De Coster[®]', 'Jonabel Jonagold', 'Novajo', 'Red Jonaprince (Red Prince[®])', 'Marnica', 'Jonagold Boerekamp (Early Queen[®])'. Most were selected for a superior amount or intensity of red colour, but differences in fruit or tree shape, time of maturity and yield have sometimes been reported.

4.2.8 'McIntosh'

'McIntosh' is a chance seedling discovered in 1811 on the farm of John McIntosh near Dundela, Ontario, Canada (Upshall, 1970). Originally called 'Granny's apple', it was renamed 'McIntosh Red' in 1836, later shortened to 'McIntosh'. Although 'McIntosh' grafts were sold as early as 1835 (Upshall, 1970), many references give 1870 as the date of commercial introduction (Beach *et al.*, 1905b; Smith, 1971; Bultitude, 1983; Proctor, 1998). The cultivar did not become popular until around 1900, about the time that the first scab sprays were developed. The parentage of 'McIntosh' is a mystery, but its vegetative characteristics, cold-hardiness and scab susceptibility have fuelled speculation that the parents may include 'Fameuse' ('Snow Apple'), 'Fall St Lawrence' or the Russian cultivar 'Alexander' (Upshall, 1970; Khanizadeh and Cousineau, 1998). After a severe winter in 1933/34 killed many 'Baldwin' trees in the north-eastern USA, they were replaced with the more cold-hardy 'McIntosh' (Smock and Neubert, 1950).

'McIntosh' is the leading cultivar in the north-eastern USA and eastern Canada and is important in eastern Europe. *Synonym*: 'McIntosh Red'.

4 2 8 1 Tree

Moderately vigorous, spreading, with good branch angles, spurs freely, type III in the Lespinasse system. Precocious, annual or alternate bearing, productive, very susceptible to preharvest drop. Cold-hardy to at least USDA zone 4a (-34°C) (Strang and Stushnoff, 1975). 'McIntosh' blooms in early-mid season, ~5 days before 'Golden Delicious'. It is more resistant to bloom frost than 'Golden Delicious', 'Delicious' or 'Jonagold', but less resistant than 'Cox's Orange Pippin' (Sj  stedt (1978), as cited by Nybom, 1992; Mittelstadt, 1989). The lethal temperature resulting in 50% death of flowers was estimated as -3.1°C (Mittelstadt and Salzer, 1989). 'McIntosh' has a high chilling requirement, ~1300 units (Ghariani and Stebbins, 1994). Tests in the former USSR suggest that 'McIntosh' is fairly resistant to heat and drought (Khalin and Shcherbatko, 1990).

4 2 8 2 Fruit

See Beach *et al.* (1905b), Smock and Neubert (1950), Smith (1971) and Bultitude (1983). Harvested 125–145 DAFB (about 4 weeks before 'Delicious') in one or two picks. Size medium to large; round to oblate; size and shape uniform or slightly irregular, with slight to no ribbing (Plate 4 8). Stem cavity medium in width and depth, broadly furrowed, acute to acuminate, partly lined with fine brown russet. Stems short, level with base, rarely exerted. Calyx basin medium in width and depth, smooth or slightly ribbed, sometimes with small fleshy beads. Eye small, tightly closed to very slightly open. Skin thick but tender, subject to stem punctures, separates readily from flesh, smooth, covered with conspicuous lilac bloom, glossy when buffed. Ground colour green to yellow-green, 30–80% deeply flushed with bright red (sometimes dark, nearly purple overcolour) and faintly streaked with short broken carmine stripes. Skin green where shaded. Flesh white, tinged with green or pink, sometimes veined with red, fine, very tender, juicy, firm but soon becoming soft. It is best adapted to cool areas with cold nights and clear autumn days. In warm areas, it has poor colour, excessive preharvest drop and soft flesh. Sensitive to bruising. Characteristic aromatic perfumed flavour, sprightly tart-sweet becoming nearly sweet. Very distinctive scent. Flesh browns quickly after cutting.

USES Mainly dessert. Flesh disintegrates when cooked. Poor to fair for sauce, fair to good for juice if mature, usually blended (Smock and Neubert, 1950; Upshall, 1970). Low susceptibility to browning after heat treatment for minimally processed slices (Kim *et al.*, 1993a).

4.2 8.3 Storage and postharvest

'McIntosh' stores 2–3 months in air (Smock and Neubert, 1950), limited by susceptibility to flesh softening, scald and chilling sensitivity. It develops internal disorders (core flush, brown heart) below 2°C and can also

become mealy in storage (Smock and Neubert, 1950). The range of optimum conditions in CA is 1.5–4.5% O₂, 1.0–5.0% CO₂, 1.7–3.0°C, for storage of 5–8 months (Kupferman, 1997). Scald control measures include DPA and air separation/N₂ purges in CA. High CO₂ injury can occur above 10% CO₂ (Watada and Abbott, 1985). 'McIntosh' is susceptible to *Coprinus* rots in storage (Meheriuk and McPhee, 1984).

4.2.8.4 Production notes

'McIntosh' is not prone to sunburn. It has poor colour if night temperatures are too high or nitrogen fertilization is excessive, and is highly susceptible to preharvest drop.

'McIntosh' is highly susceptible to scab, up to 100% of the fruit may be unmarketable due to scab if unsprayed (Ellis *et al.*, 1998). Susceptibility to fire blight and powdery mildew is rated as low to moderate, depending on the region. 'McIntosh' is resistant to cedar-apple rust, quince rust and hawthorn rust (Aldwinckle, 1974; Warner, 1992). It is also resistant to race 2 but not race 1 of apple rust in Japan (Sakuma, 1985). 'McIntosh' is susceptible to a number of other fungal diseases, including *Nectria* canker (Bultitude, 1983; Grabowski, 1994; Braun, 1997), brown rot (Cimanowski and Pietrzak, 1991) and black-rot canker (Miller, 1973). However, it shows partial resistance to *Pezizula* bark rots (Kucmierz *et al.*, 1985) and *Alternaria* leaf blotch (Sawamura, 1972) and good resistance to brown leaf spot (Koropatnyuk, 1974). It expresses only mild symptoms when bud-inoculated with apple mosaic virus (Singh *et al.*, 1981).

'McIntosh' is heterozygous for a gene involved in resistance to rosy leaf-curling aphid (Alston and Briggs, 1977). It has a degree of resistance to apple leaf miner (Maciesiak, 1996) and apple rust mite (Kozłowski and Boczek, 1987), but is susceptible to red mite (Bielak and Dabrowski, 1986).

4.2.8.5 Breeding

'McIntosh' is one of the top five most frequent founding clones of modern apple

cultivars (Noiton and Alspach, 1996). It has been used for breeding mainly in Canada, the USA and eastern Europe (including Russia), with some use in the UK. Offspring include 'Lobo', 'Melba', 'Summerred', 'Spartan', 'Cortland', 'Empire', 'Macoun' and 'Tydeman's Red'. While some of these have substantial regional importance, none has yet surpassed 'McIntosh' in commercial trade volume. The scab-resistant cultivars 'Liberty', 'McShay', 'Belmac', 'Richelieu', 'Enterprise', 'Murray' and many others also count 'McIntosh' in their parentage. Columnar apples with 'Wijcik McIntosh' in their parentage include 'Telamon', 'Tuscan', 'Trajan', 'Golden Sentinel', 'Scarlett Sentinel' and others from various European breeding programmes. Breeders from the former USSR reported that 'McIntosh' shows high general combining ability for winter-hardiness (Savel'ev and Yakovlev, 1981).

4.2.8.6 Sports

Standard-habit strains have been selected for improved colour, earlier colour and/or earlier maturity and better storage, e.g. 'Rogers Red McIntosh', 'Cornell McIntosh', 'Summerland McIntosh', 'Imperial All Red McIntosh', 'Marshall Mac', 'Redmax®'. They vary in stability, vigour, yield, quality and tendency for preharvest drop (Dzieciol *et al.*, 1988; Kruczynska *et al.*, 1991). 'Pioneer Mac' is not a sport, but an open-pollinated seedling of 'McIntosh' (Brooks and Olmo, 1997). Several spur types have occurred as spontaneous limb mutations, e.g. 'Mor-spur McIntosh', 'MacSpur McIntosh', 'Dewar McIntosh' ('Starkspur Ultramac'), 'Wijcik McIntosh' ('Starkspur Compact Mac'). 'Wijcik McIntosh' is unique not only for its columnar shape (classic type 1 in the Lespinasse system), but because it is the only known mutation of apple capable of transmitting compact spurry habit to its offspring. The trait is believed to be determined by a single dominant gene, with some modifiers (Lapins, 1974, 1976). Commercially, standard types are more popular than the spur mutants.

4.2.9 'Rome Beauty'

'Rome Beauty', a chance seedling of unknown parentage, was discovered by H.N. Gillett of Proctorville, Ohio, USA, in 1816 (Mowry, 1970). 'Rome Beauty' was named after the township in which it was discovered and was introduced in 1848. Production is declining in most areas, but it is still important in certain regions, such as New York State and southern Europe. *Synonyms*: 'Gallia Beauty', 'Belle de Rome', 'Faust's Rome Beauty', 'Gillett's Seedling', 'Morgenduft'.

4 2 9 1 Tree

Moderately vigorous, initially upright, becoming spreading and drooping, terminal bearing, does not spur readily. Acrotonic tip-bearing habit, type IV in the Lespinasse system. Much blind wood. Moderately precocious, annual bearing, productive, diploid, slightly self-fertile. Not subject to preharvest drop. Moderately cold-hardy (Khanizadeh and Cousineau, 1998; Luby *et al.*, 1999). High chilling requirement, ~800–1100 h (Tabuenca and Jimenez, 1984). Blooms late season, usually escaping frost.

4 2 9 2 Fruit

See Beach *et al.* (1905a), Mowry (1970), Bultitude (1983) and Khanizadeh and Cousineau (1998). Harvested 3 weeks after 'Delicious', 160–175 DAFB (Mowry, 1970; Khanizadeh and Cousineau, 1998) in a single pick. Size usually large; round to round-conic, sometimes slightly oblong or oblate, slightly flattened at base (Plate 4.9). Size and shape uniform. Regular or faintly ribbed. Stem cavity smooth and russet-free, wide, moderately shallow to fairly deep, often gently furrowed. Stems long, often inserted at an angle, well exerted from fruit base. Calyx basin medium in width, shallow to moderately deep, slight traces of ribs, russet-free. Eye partly to fully open. Skin thick, tough, smooth, glossy, becoming greasy. Ground colour yellow-green, becoming pale yellow. Original strain 50–80% striped and mottled bright orange-scarlet red with some broken, fairly wide carmine stripes. Lenticels small,

moderately conspicuous green, brown or white dots (Beach *et al.*, 1905a; Bultitude, 1983). Flesh nearly white with green tinge, firm, slightly to moderately juicy, a little coarse, mealy if overripe. Flavour sweet subacid, slightly aromatic, quality mediocre, sometimes lacking in flavour. Exceptional ability to withstand handling.

USES See Smock and Neubert (1950) and Root (1996). Fair for dessert, good for culinary use, good for dehydration, fair to good for juice and processing. Sauce of poor colour and runny, usually blended with other cultivars (Root, 1996). Good shape and uniformity for mechanical peeling.

4.2.9.3 Storage and postharvest

Storage and shelf life are short for a late-harvest apple, 4–5 months in air. 'Rome Beauty' has a strong tendency to become mealy in storage. Recommended CA conditions are 1% O₂, 0% CO₂, 0°C for storage of 7–9 months (Kupferman, 1997). 'Rome Beauty' may get superficial scald; it is controlled commercially with DPA, low O₂, or air separation/N₂ purges of the CA room (Kupferman, 1997). 'Jonathan spot' is eliminated by CA (Smock and Neubert, 1950).

4.2.9.4 Production notes

'Rome Beauty' shows moderate to high susceptibility to apple scab, fire blight, powdery mildew and cedar-apple rust. It is moderately susceptible to quince rust (Aldwinckle, 1974; Warner, 1992) and susceptible to black-rot canker/frog-eye leaf spot (Miller, 1973). It is resistant or highly resistant to bitter rot, *Nectria* canker (Khanizadeh and Cousineau, 1998) and crown rot (Aldwinckle *et al.*, 1975). Fruit finish is adversely affected by high precipitation and high temperature (Mowry, 1970). 'Rome Beauty' is prone to scarf skin, which is particularly noticeable on red strains. It is not prone to sunburn. 'Rome Beauty' is more susceptible than 'Delicious' or 'Golden Delicious' to fruit injury from tufted apple-bud moth (Knight and Hull, 1988). It has a degree of resistance to woolly apple aphid (Asante, 1994).

4.2.9.5 Breeding

'Rome Beauty' offspring include 'Jerseyred', 'Ben Hur', 'Roanoke' and other cultivars of minor importance (Mowry, 1970). It appears frequently in the parentages of modern apple cultivars, although it is not in the top five founding clones (Noiton and Alspach, 1996). Probably its most lasting breeding legacy is in scab-resistant cultivars. 'Rome Beauty' was the first parent crossed with *Malus floribunda* 821 in the scheme used to bring the V_f scab-resistance gene into commercial apple cultivars. All offspring of this scab-resistant line therefore carry 'Rome Beauty' genes.

4.2.9.6 Sports

'Cowin Rome Beauty', 'Law Red Rome', 'Starkspur Red Rome', 'Taylor Flamespur', 'Cowin Red Rome' ('Double Red Rome') (tetraploid). Most strains have improved colour; a few are slightly spurrier, e.g. 'Lawspur® Rome', 'Compact Red Rome'. Strains vary in fruit shape (Brooks and Olmo, 1997), tree size, spurriness, propensity to flower on 1-year-old wood, fruit size, flower-cluster density, susceptibility to scarf skin (Smith, 1971; Ferree, 1994).

4.2.10 'Braeburn'

'Braeburn' is a chance seedling introduced by O. Moran of Nelson, New Zealand, in 1952. Its parentage may be 'Lady Hamilton' OP (Brooks and Olmo, 1997) or 'Lady Hamilton' × 'Granny Smith' (Khanizadeh and Cousineau, 1998). New Zealand is the world's main producer of 'Braeburn'; other producers are Argentina and Chile. Production is increasing in the USA and Europe.

4 2 10 1 Tree

Low to moderate vigour, very spurry, spreading, type II in the Lespinasse system. Extremely precocious, capable of flowering in year of planting and susceptible to stunting if cropped then. Productive, suitable for high-density planting, but can be biennial

bearing. 'Gala' and 'Fuji' may yield more (Stebbins, 1990). Chilling requirement medium, ~1140 units (Ghariani and Stebbins, 1994). Blooms profusely in mid-season, diploid; not self-fertile but sets heavily. Blooms on 1-year-old wood and spurs. Very sensitive to chemical thinners (Waliser, 1994).

4 2 10 2 Fruit

Harvested 150–170 DAFB, about a week before 'Fuji' or 'Rome Beauty', in several picks (Khanizadeh and Cousineau, 1998). Not susceptible to preharvest drop. Size medium to large; conic to round-conic, more elongated in cooler regions, with definite crowning at apex (Plate 4.10). Stem cavity medium in width and depth, usually partly lined with green or brown russet. Stems medium to medium-long, even to exerted. Calyx basin wide, medium in depth, distinctly ribbed. Eye closed or a little open. Lenticels small, conspicuous tan or green dots. Skin glossy, greenish yellow with short, dark crimson stripes overlaid with dark scarlet blush. Only well-exposed fruit have good colour. Flesh cream, very juicy, very firm and crisp, slightly coarse. Flavour sprightly tart-sweet, pleasantly aromatic, refreshing. Flesh browns slowly when cut (Khanizadeh and Cousineau, 1998).

USES Appears to be limited to fresh market at this time

4.2.10.3. Storage and postharvest

'Braeburn' is susceptible to bitter pit and other calcium-related disorders in 'off' years. It is also prone to water-core, core browning, lenticel blotch and superficial scald. The latter is controlled with DPA or ULO storage (Kupferman, 1997). 'Braeburn' will keep for 130 days in air storage (Khanizadeh and Cousineau, 1998). CA recommendations are strongly influenced by the prevention of 'Braeburn browning disorder' (BBD), a CO₂-related severe internal browning. The symptoms (dry or water-soaked cortex browning and dry, lens-shaped, internal cavities) develop in the first 2 weeks of CA or even on the tree and are not always visible externally

(Elgar *et al.*, 1998). Texture remains firm. Preharvest causes are not understood. The incidence rises with high CO₂ or low O₂ partial pressure in CA, rapid imposition of CA, cooler climates/seasons or higher altitude of orchard, advanced maturity, lightly cropped trees, and other unidentified factors (Elgar *et al.*, 1998; 1999; Lau, 1998). BBD is not a low-temperature injury (Lau, 1998) or a mineral-nutrient disorder (Elgar *et al.*, 1999), but may be related to the cultivar's unusually high flesh density (Lau, 1998). Storing 'Braeburn' in air at 0°C for 2 weeks prior to CA appears to reduce BBD (Elgar *et al.*, 1998). Optimum conditions vary with region, ranging from 1.0 to 3.0% O₂, <0.5 to 1.5% CO₂, -0.5 to 1.5°C, for 6–9 months of storage (Kupferman, 1997).

4.2.10.4 Production notes

'Braeburn' is susceptible to scab, powdery mildew and fire blight. It is susceptible to apple scar skin viroid (Desvignes *et al.*, 1998). It is very susceptible to red mite. Other disease and insect reactions have not yet been reported.

4.2.10.5 Breeding

'Braeburn' is currently in use for breeding in New Zealand, North America and elsewhere. 'Scifresh' is an offspring of 'Braeburn'.

4.2.10.6 Sports

Recent red sports include 'Hillwell (Hidala) Red Braeburn', 'Lochbuie™ Braeburn', 'Joburn™ Braeburn' and others. All offer improved red colour and some are claimed to ripen earlier.

4.2.11. 'Elstar'

Selected by T. Visser and others, Wageningen, The Netherlands, from a cross of 'Ingrid Marie' × 'Golden Delicious' made in 1955, 'Elstar' was named in 1972 and introduced commercially in 1975. It is the main cultivar in The Netherlands and is also planted in Germany, Belgium, Italy, Denmark, France, England, Switzerland, Austria, Poland and

the USA. Useful descriptions appear in Götz and Silbereisen (1989), Friedrich and Petzold (1993), Manhart (1995), Khanizadeh and Cousineau (1998) and Anon. (1999). *Synonym*: 'Lustre Elstar™'.

4 2 11 1 Tree

Vigorous, with a strong central leader, spreading, medium-thick branches, with many water shoots causing a dense, bushy tree; naturally well feathered, intermediate between type II and III in the Lespinasse system. Leaves medium to large, very late leaf fall. Precocious, productive, strong tendency to biennial bearing. Bears on 2- and 1-year-old wood and somewhat on spurs. Blooms mid-season, diploid with fertile pollen, somewhat self-fertile, but cross-pollination required. Suitable pollinizers are listed in Kemp (1996). Medium susceptibility to bloom frost. Bark and shoot tips susceptible or very susceptible to winter injury (Goddrie, 1985; Fankhauser and Stadler, 1986), the latter due to the late cessation of vegetative growth. Chilling requirement ~1200 units (Gharani and Stebbins, 1994).

4 2 11 2 Fruit

Harvested 130–150 DAFB, multiple pick. Picks fairly easily, very little preharvest drop. Flesh creamy white to yellow, sometimes slightly greenish, crisp and fairly firm, juicy, fine- to medium-textured, balanced sweet-tart apple with pleasant strong aromatic flavour. Acidic at harvest, later more mellow. Usually symmetrical and regular, round-conical, sometimes slightly flattened (Plate 4.11). With good light exposure, an attractive, somewhat orange, bright red, sometimes slightly pinkish, striped to solid blush on a green-yellow background, becoming yellow. Firmness, crispness and taste strongly depend on proper harvest date. Usually some russet in basin and stem cavity, the latter often streaking over shoulder. In some years, severe netted to solid, rather coarse, russet on cheeks (Wagenmakers, 1999). Basin medium in depth and width, ribbing fine to medium, apex slightly ribbed. Eye medium, half open. Stem cavity rather wide and quite

deep, with medium to long, rather slender but sometimes partly thick stalk; fleshy stalks and twinned fruits can occur. Skin almost smooth, rather dull, somewhat waxy, moderately greasy with full ripeness, medium thick, rather tough. Low bruising susceptibility. Shelf life fairly good

USES Especially good for fresh consumption, good for salads, juice and baking, only moderately suitable for sauce.

4.2.11.3 Storage and postharvest

'Elstar' stores at 1°C for 3 months in air or for 5 months at 1°C in scrubbed CA where both CO₂ and O₂ are not above 3%. It can be stored in ULO at 1°C for 7–7.5 months at 1.2% O₂ and 2–3% CO₂, provided picked at proper time. Ripe fruit from susceptible plots is stored at 2°C because of the risk of internal browning. 'Elstar' is susceptible to shrivelling, slightly susceptible to bitter pit and moderately susceptible to scald in high CO₂. LTB and internal browning (Verschoor and de Jager, 1998) can occur, the latter enhanced by low storage temperature, certain growing sites, late picking, long storage, high CO₂, high relative humidity and plentiful blush. Red mutants seem to be more prone, as do lateral fruits from 1-year-old wood (van der Laken and Verschoor, 1998, van Schaik and Schoorl, 1999). Excessive internal browning seems to be mainly due to storage below 0–0.5°C (van Schaik and Schoorl, 1999).

In long-term storage, 'Elstar' is susceptible to *schilvekjes* (skin spots), which seem to be related to scald. The occurrence varies with year. The spots, limited to the surface but spreading over the fruit, occur mainly on the shaded side of the fruit. Relatively unripe, poorly coloured fruit from the inner canopy are more prone; growing site also has an influence. DPA can reduce the incidence (Roelofs, 1997). A relatively high level of moisture removal during storage seems to be effective for control; high humidity exacerbates the problem (van der Valk and Tomassen, 1999). Susceptible lots are best segregated for short storage at low temperature: 0.5°C, 1.2% O₂ and 0.5% CO₂

4.2.11.4 Production notes

In areas with small preharvest diurnal temperature differences, poor colour is common. Summer pruning, approximately 2 weeks before harvest, enhances blush. Redder sports can also prevent this problem, but 'Elstar' is still a cultivar best suited to cool climates; elsewhere fruit will be too soft. For good storage and colour, repeated selective picking is required. In low-crop years, a leaf condition resembling Cox's disease can occur, in which many shoots have light green leaves. Accurate and timely thinning is essential to prevent biennial bearing (Wertheim, 1998; Wertheim *et al.*, 2001) and for optimum size and taste. Russet can be reduced with GA₄₊₇. Late leaf fall and soft shoot tips increase scab risk; late sprays against *Nectria* canker are required due to late leaf fall. Fruit from open trees are less prone to skin spots and fruit from vigorous or poor-yielding trees are more prone to internal browning.

'Elstar' is susceptible to mildew, scab and *Nectria* canker (Kemp and van Dieren, 1998). In north-western Europe, mildew susceptibility is no worse than in 'Jonagold', but in the USA the opposite is true. 'Elstar' is tolerant of apple scar skin viroid (Desvignes *et al.*, 1998) and susceptible to brown rot, crown rot and sunburn. Some June-drop fruit remain on the tree as mummies (Knoche *et al.*, 2000).

4.2.11.5 Breeding

'Elstar' has been used as a parent in The Netherlands (Janse and Verhaegh, 1990) and also by German, French, Italian and Swiss breeders. The scab-resistant (*V_p*) cultivars 'Ecolette' (also resistant to powdery mildew), 'Santana', 'Gerlinde', 'Ahrista' and 'Dalinbel' ('DL 11') have resulted, as well as a series of promising numbered selections.

4.2.11.6 Sports

'Elstar' mutates easily. Since the first sport, later called 'Red Elstar', was found by Mr L. Michielsens (Rilland-Bath, The Netherlands, 1981), an ongoing series has been tested and introduced, mainly for colour pattern and intensity, but also growth habit, fruit shape,

firmness and ripening time (Goddrie, 1996). Goddrie and Kemp (1992) and Kemp *et al.* (1994) list over 40 sports and Stehr and Clever (1995) list 25, but over 75 are now known.

4.2.12 'Cox's Orange Pippin'

'Cox's Orange Pippin' originated in 1825 on the property of Richard Cox, in Buckinghamshire, UK. It is believed to be a seedling of 'Ribston Pippin'. 'Cox's Orange Pippin' was introduced in 1850 and was first grown commercially about 1862. In the early 1900s, its popularity waned due to disease susceptibility, but, after the introduction of lime sulphur in the 1920s, it regained commercial interest and, since the 1970s, it has been the most important English apple. It is also grown in The Netherlands, Germany, Belgium, New Zealand, Australia, France, Sweden, Denmark and Switzerland. Good descriptions can be found in Baldini and Sansavini (1967), Nilsson (1987), Sanders, (1988), Götz and Silbereisen (1989), Friedrich and Petzold (1993), Morgan and Richards (1993), Manhart (1995) and Khanizadeh and Cousineau (1998). *Synonyms*: 'Cox(s) Orange', 'Cox's Orangen Reinette', 'Kemp's Orange', 'Orange de Cox' and many others (see Smith, 1971)

4 2 12 1 Tree

Moderately vigorous to vigorous, rather open, naturally very well feathered, spreading-upright, rather slender, long wood. Bears on 2-year-old wood, spurs and 1-year-old wood. Type III in the Lespinasse system. Precocious, moderately productive, medium tendency to biennial bearing; thinning required for sufficient size and to prevent biennial bearing (Child *et al.*, 1986, Wertheim, 1986; Tromp, 2000). Leaves often with necrotic spots; early leaf fall can occur, especially after a warm, dry period. Blooms mid-season, diploid, fertile pollen. Somewhat self-fertile (Hall and Crane, 1933), but cross-pollination required. Suitable pollinizers are listed by Kemp (1996). Susceptible to bloom frost, very susceptible to winter injury. Chilling requirement ~1300 units (Gharani and Stebbins, 1994).

4 2.12 2 Fruit

Harvested 130–150 DAFB, picks easily, some preharvest drop. Needs full ripeness for optimum taste. Firmness, crispness and taste strongly depend on proper harvest date. Size medium, with a slightly brownish, orange-red blush and broken stripes over a pale yellow-green background, becoming clear yellow. Colour optimum with some cool nights shortly before harvest. Often russeted, varying with year; dots and patches of fine to coarse russet, sometimes with cracks. Sometimes considerable russet in basin and stem cavity, occasionally streaking out. Usually dull, dry skin, sometimes medium waxy, fairly smooth. Shape round-conical to oblate, usually symmetrical (Plate 4.12). Slightly ribbed at basin and apex. Eye fairly small to medium, half open, calyx closed. Basin medium wide, rather shallow. Stems usually medium thick, rather short, in a fairly broad and medium deep cavity; king fruits often have a fleshy stalk. Flesh greenish yellow to deep cream, juicy, firm and crisp, fine-textured; low bruising susceptibility. Sweet, slightly subacid, with a characteristic, rich, aromatic, complex flavour, with notes of nut, pear and banana. Shelf life good. Skin moderately thick, slightly tough.

USES Very good for dessert and cider, preferably blended with others for juice and sauce; unsuitable for salad and pie

4 2.12.3 Storage and postharvest

Large fruit from poorly cropped trees are almost unsuitable for storage. 'Cox's Orange Pippin' stores for 3 months at 3.5°C in air. It is susceptible to LTB below 3.5°C and CO₂ damage above 1%. 'Cox's Orange Pippin' can be stored in scrubbed CA at 3.5°C, <1% CO₂ and <3% O₂ for 5 months. Stores in ULO 1.2–4% O₂, <0.7% CO₂ at 4°C for 6.5 months. ULO is preferred to reduce brown core. It is susceptible to bitter pit, softening, internal browning, water core, brown core, LTB and shrivelling. Scald incidence varies from low to moderate, depending on year. Early picking increases bitter pit and LTB

4.2.12.4 Production notes

Best tree condition, cropping and fruit quality are achieved with good soil and where summers are cool; it reacts very negatively to all disturbances in climate, water and nutrition. Especially on weaker rootstocks, Cox's disease can occur: mid-shoot necrotic leaf spot followed by leaf fall, reddish-purple leaves, blind wood formation and reduced productivity. This condition can be reduced by an interstem and stem scoring. Interstems are also effective against collar rot. Standard 'Cox's Orange Pippin' often lacks colour. Necrotic leaf spot and leaf fall can be reduced by leaf application of magnesium and manganese. Cross-pollination (Goldschmidt-Reischel, 1996) and proper thinning (Wertheim, 1986) are required for adequate size and regular cropping. Severe June drop can occur (Wertheim, 1973). GA sprays can induce parthenocarpic fruit (Kotob and Schwabe, 1971). Russetting and rain cracking can be reduced by GA₄₊₇. Several weekly sprays with calcium are required to prevent softening and bitter pit (Sharples and Johnson, 1977). It is susceptible to damage from sulphur sprays.

'Cox's Orange Pippin' is susceptible to mildew, collar rot, brown rot and bitter rot, moderately susceptible to scab (Kemp and van Dieren, 1998) and very susceptible to *Nectria* canker, and therefore not suitable for cold, wet areas. It has low susceptibility to rosy apple aphid and rosy leaf-curling aphid (Alston and Briggs, 1977; Graf *et al.*, 1992).

4.2.12.5 Breeding

Because of its characteristic aroma, 'Cox's Orange Pippin' has often been used in breeding and is one of the top five most frequent founding clones of modern apples (Noiton and Alspach, 1996). Offspring include 'Fiesta' ('Red Pippin'®) and 'Meridian' from the UK, 'Elise' ('Roblos'®), 'Karmijn de Sonnaville', 'Ivette' and 'Zoete Oranje' (a low-acid cooking apple) from The Netherlands, the Czech cultivar 'Šampion' and the Yugoslavian 'Pohorka'. Smith (1971) lists 110 offspring, including 'Winston', 'Holsteiner Cox' ('Holstein'), 'Ingrid Marie'

(probably) and 'Kidd's Orange Red'. It has also been used in France and Germany. 'Elstar' and the scab-resistant American cultivar 'Suncrisp'® are F₂ offspring.

4.2.12.6 Sports

Götz and Silbereisen (1989) list over 40 sports and mutants, and more than 30 are mentioned by Kemp *et al.* (1998), mainly based on colour. The English irradiation programme in the 1970s produced many mutants, among them some self-fertile 'Queen Cox' clones (Campbell and Lacey, 1982); other irradiated clones came from Germany (Götz and Silbereisen, 1989) and New Zealand (Manhart, 1995). In The Netherlands, a heat-treated virus-free clone of 'Cox's Orange Pippin' called 'T12' (top graft) was introduced in 1975 and is considered the standard 'Cox's Orange Pippin'. Well-known sports include: 'Cherry Cox', 'Cox Rouge des Flandres', 'Crimson Cox', 'Queen Cox', 'Korallo', 'Kortegård Cox', 'Kummer Cox', 'Ottensen Cox', 'Moje Cox', 'Hauschildt Cox', 'Ley 36.72', 'Clone 18', 'Cox la Vera', 'Red Cox' and 'Flikweert'.

4.3 Outlook

World apple production is predicted to rise faster than population growth in the near future (O'Rourke, 1998a). Massive production in China and new cultivars will have a major global impact in the coming century. The key 'new' cultivars ('Fuji', 'Gala', 'Braeburn') are expected to increase in production and trade volume over time as more high-density plantings come into full production. 'Delicious', 'Golden Delicious', 'Cox's Orange Pippin', 'Rome Beauty', 'Jonathan', 'McIntosh' and perhaps 'Granny Smith' are losing ground to these and other new cultivars because of changes in market demand and consumer preference (O'Rourke, 1998b). With the exception of 'Braeburn', these rising cultivars are all the products of breeding programmes. Some groups are moving to control the availability of their cultivars to limit production and maintain fruit prices (e.g. in

'variety clubs'). Disease-resistant cultivars have yet to achieve any major commercial importance. Probably the increasing emphasis on pesticide reduction and heightened efforts of breeding programmes to combine good eating quality with resistance will change this trend in coming decades, at least in the European Union.

Cultivars of increasing interest that are being grown in more than one country now include: 'Cripps Pink'/'Pink Lady'® ('Lady Williams' × 'Golden Delicious', Australia), 'Honeycrisp'™ (unknown parentage, USA), 'Corail'/'Pinova'™ ('Clivia' × 'Golden Delicious', Germany), 'Delblush'/'Tentation'® ('Golden Delicious' × 'Blushing Golden',

France), 'Topaz' (V_f, 'Rubin' × 'Vanda', Czech Republic), 'Pacific Rose' ('Gala' × 'Splendour', New Zealand), 'GoldRush' (V_f, 'Golden Delicious' × 'Co-op 17' USA) and 'Ambrosia' (chance seedling, Canada). Whether they will ultimately displace major cultivars now in the ground remains to be seen.

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5 Apple Rootstocks

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5.1 Introduction

A rootstock constitutes the root system and a small proportion of the lower trunk (sometimes referred to as the shank) of most apple trees. Grafting the genetically distinct fruiting part of the tree, the scion, on to the rootstock forms the whole tree (or stion). Occasionally, a third genetically distinct component, an interstock or interstem, is grafted between the rootstock and the scion (Fig. 5.1).

It is thought that rootstocks have been used as an aid in the propagation of apple trees for more than 2000 years. The principal reason for their use is the difficulty in propagating selected cultivars of apple scions on their own roots. Although apple trees can be propagated quite easily from seed (pips), the resulting trees are extremely variable in vigour, habit and fruit characteristics; most apple trees raised from seed are vigorous and bear fruits of poor size, appearance and quality. This is because of the heterozygous nature of *Malus pumila* Mill. Unfortunately, therefore, trees propagated from seeds collected from an apple tree exhibiting desirable fruiting characteristics will not be true to type.

Although apple scions can with some difficulty be propagated from layers, the technique is difficult and the multiplication of scion trees using this technique is extremely slow. Traditional methods of propagation using cutting techniques are generally

unsuccessful when used for propagating apple-scion cultivars. In contrast, the rootstocks used for apple tree propagation can in most instances be propagated easily and cheaply, either from seed or from simple layering or cutting techniques. These rootstocks are then used to multiply selected scion cultivars of apples by employing grafting or budding techniques (see Chapter 6). Although new improved methods of propagation based on cutting techniques (including misting, fogging, heated bins and micropropagation) have in recent years led to successful techniques for propagating apple scions on their own roots (see Chapter 6), these have yet to be adopted by commercial nurserymen. Rootstocks continue to be used as a principal aid to the propagation of apple scions.

Rootstocks may also confer many other benefits, in terms of the growth and cropping of the scions grafted on them. Selected rootstocks, especially clonal selections, may be used to control the intrinsic vigour of the scion, its habit, its precocity and efficiency of cropping and the quality of fruits produced. Rootstocks may also be used to adapt scions to unfavourable environmental (climatic and soil) conditions and against aerial and soil-borne pests and diseases.

Interstocks or interstems are occasionally used in propagating apple trees. These are usually clonal and genetically distinct from the scion and the rootstock. They are used for aiding the control of tree vigour, stimulating precocious fruiting and improving the branching of young nursery trees and to increase resistance against trunk diseases or winter cold injury.

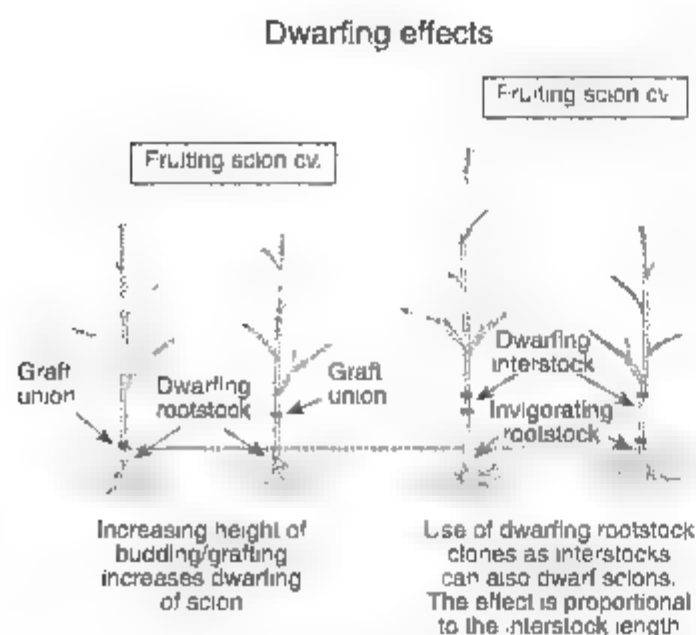


Fig. 5.1. Influence of height of budding or dwarfing interstock on the vigour of scion growth

5.2 Species, Cultivars and Sub-clones Used as Rootstocks for Apples

The apple rootstocks used throughout the world are, like the fruiting apple scions, classified by taxonomists as *M. pumila* Mill. (or alternatively as *Malus × domestica* Borkh.). Most plant taxonomists believe that the cultivated apple and its rootstocks are derived from a hybrid of several species formed centuries ago close to Almata (Alma Ata) in

Kazakhstan, where natural forests of *Malus* predominate. These hybrids were then spread, possibly by animals such as bears but almost certainly by humans, along the Silk Route into Persia, where horticulturists domesticated them. Later, the superior and/or useful selections were spread much further within the extensive Roman Empire. Currently, however, there is little DNA evidence to support the contention that the domesticated apple is a hybrid, and some botanists now believe that the cultivated apples and their rootstocks are in fact all similar to the wild apples, now referred to by some apple taxonomists as *Malus sieversii* (Ledeb.) Roem.

In contrast, the rootstocks used for propagating many stone fruit species (peaches, apricots, cherries and plums) are of different species from the fruiting scion species, and some may be hybrids developed by plant breeders. Even a different genus, the quince (*Cydonia oblonga* L.), is widely used as a rootstock for European pears (*Pyrus communis* L.). The only species other than *M. pumila* (including *M. sieversii* and *M. × domestica*) that is widely used as a rootstock for apples is *Malus prunifolia* (Willd.) Borkh. Seedlings of this species are used as rootstocks in parts of China.

The use of different *Malus* species as rootstocks for apples was first suggested in the west by Sax (1949), but they had already been used for centuries in eastern countries, such as China. One of the problems with using seedling-raised rootstocks has always been their rather variable effects on scion growth and cropping. Luckwill and Campbell (1954) suggested using apomictic seedlings of *Malus* species to give more uniformity of performance. Apomictic seeds are derived only from the maternal tissues and are homozygous and very uniform in performance as rootstocks. Campbell and Wilson (1962) continued this work on apomicts, focusing on *Malus hupehensis* (Pamp.) Rehd. and *Malus toringoides* (Rehd.) Hughes. Apomictic seedlings of hybrids between *M. × domestica* and *M. hupehensis*, *Malus sargentii* Rehd. or *Malus sieboldii* (Reg.) Rehd., all of which are cheap to propagate, are free from virus and have uniform effects on scion growth and cropping, have also been tested

as rootstocks for apples (Schmidt, 1988). However, absence of any vigour control and difficulties in separating the apomictic from the non-apomictic seedlings have made this rootstock option unpopular with commercial nurserymen and fruit growers.

Horticulturists have, over the last 150 years or more, bred and selected many cultivars of clonal rootstocks. Some of the first rootstock cultivars were selected as chance seedlings from wild populations of apples. More recently, fruit breeders have made controlled crosses and selected from the resulting siblings. All of these rootstock cultivars, with the exception of the apomicts mentioned above, must be propagated vegetatively. Selections within the cultivar have also been made, especially with the rootstock M.9, where 'sub-clones' differing slightly in their individual characteristics have been distinguished. Although genetically similar, these 'sub-clones' differ slightly in their ability to propagate and in their effects upon scion vigour.

5.3 Methods of Rootstock Propagation

Traditionally, one method of propagating rootstocks was to dig up suckers from around the bases of mature apple trees. This method is no longer used and is not to be recommended due to the possibility of virus transmission via the rootstock to the new scion tree. More often, seeds of apples collected in the wild or from orchard trees were used for propagating rootstocks. Such rootstocks, although cheap to propagate, were mostly very invigorating and also very variable in their effects on scion growth and cropping. Apple seedlings are still used as rootstocks in some parts of the world, although today seedlings of predominantly one cultivar (e.g. 'Red Delicious' in the USA) provide slightly improved uniformity when these rootstocks are grafted with scions. They are of most value where control of the scion vigour and cropping is achieved by other methods than by using a dwarfing rootstock, but they may also be used on droughty soils where their deep root systems are of value.

Where rootstocks are needed to provide additional benefits, other than simply a means of propagating the scion, rootstocks propagated using vegetative techniques (i.e. clonal rootstocks) are essential. These rootstock cultivars, which can affect the vigour, habit and cropping performance of scions as well as adapting the scions to unfavourable environmental (edaphic and climatic) conditions, are now used for tree propagation in the majority of apple-producing countries of the world. Their propagation, by stooling, layering or cutting techniques (including *in vitro* micropropagation), is described in Chapter 6 and also in Webster (1995).

5.4 Rootstock Effects on the Growth and Cropping and the Adaptability to Environmental Conditions of Scions

Rootstocks capable of influencing scion vigour have been available to horticulturists for two millennia at least, there being evidence from ancient Persia of dwarfed apple trees grown on rootstocks. However, it is only in the last 100 years that the full potential of rootstocks for modifying scion growth and cropping and adapting trees to unfavourable environmental conditions has been recognized. This rootstock potential is still being developed in many parts of the world. For many centuries the majority of apples were produced on large standard trees grown either on their own roots or on rootstocks raised from seed or from suckers dug up from beneath mature orchard trees. Only in the gardens of European monasteries, palaces and castles and a few private gardens were smaller trees on more dwarfing rootstocks produced.

5.4.1 Rootstocks and interstocks as aids to controlling scion vigour and cropping

Choice of the appropriate rootstock and/or interstock can enable the fruit grower to control the inherent vigour of the scion tree, so making possible and facilitating the adoption of a chosen system of tree spacing, pruning and training (Ferree and

Carlson, 1987; Wertheim, 1998). Many apple rootstocks/interstocks reduce the strong vigour of scions, allowing them to be grown as dwarf, closely planted trees that are easy and inexpensive to manage. Trees grown on most of these dwarfing rootstocks/interstocks also produce fruits precociously and crop abundantly and consistently from season to season (Webster, 1994). Studies conducted in several apple-producing countries of the world have shown that, where the unit costs of labour and/or land are relatively high, controlling tree vigour with dwarfing rootstocks/interstocks greatly improves the economics of apple production. Trees of dwarf stature can also be targeted with crop-protection sprays accurately, so avoiding excessive use of pesticides and undesirable spray drift into the surrounding environment.

Use of appropriate dwarfing rootstocks/interstocks often increases the numbers of floral clusters (spur, terminal and axillary) produced per linear branch length by the scion (Ferree *et al.*, 1995). The quality of the flowers produced by these floral buds (i.e. their ability to set fruits when pollinated) can also be improved by use of certain rootstocks, although the evidence for this is often inconsistent from site to site. Rootstocks such as M9 have been reported to improve while others, such as M.27, have been reported to reduce the size of scion fruits at harvest. However, these effects are also often difficult to measure objectively, unless crop loading on trees on the different rootstocks is uniform. It is also suggested that rootstocks can influence the postharvest storage potential of apples, although this effect is also difficult to prove conclusively on account of seasonal influences and the confounding effects of the rootstock on crop load/tree and time of fruit ripening (Autio, 1991; Barden and Marini, 1992). It is generally agreed that scions on M.9 rootstocks or interstocks generally ripen up to 1 week earlier than the same scion on other more invigorating rootstocks (Hewetson, 1944), and trees on M.27 have also been reported to ripen earlier than trees on M.26 (Lord *et al.*, 1985).

5.4.2 Rootstocks for adapting scion cultivars to unfavourable environmental conditions

In many areas of the world where apples are produced commercially the environmental conditions are not fully suitable. Very severe winter cold can lead to the death of apple trees on many rootstocks and the requirement for rootstocks in many eastern European countries, Canada and the USA is for resistance to low-temperature damage. In recent years many cold-tolerant selections have become available. Although these resistant rootstocks are believed to slightly aid scion tolerance to winter cold, their main benefits are in providing the roots and trunks (shanks) of the rootstock with greater tolerance to very low temperatures. Where winter temperatures are very low for sustained periods and snow cover is minimal, rootstocks such as M.9 and M.7 are often severely damaged or even killed. In contrast, the roots of other rootstocks show better tolerance of freezing soil conditions (Czynczyk, 1974; Quamme, 1990; Quamme *et al.*, 1999).

Sensitivity to drought is a major constraint on apple production in some countries and this sensitivity may be influenced by choice of rootstock (Olien and Lakso, 1984; Higgs and Jones, 1991). Sensitivity is particularly severe on dwarfing and very dwarfing rootstocks, such as Mark, P22 and M.27. Some semi-dwarfing rootstocks, such as J.9, appear to offer some tolerance of drought conditions. By selecting rootstocks that are more tolerant of drought, apple production has been rendered more feasible in many droughty areas. Sometimes the problem is overcome by using very drought-tolerant but invigorating seedling rootstocks, as in China. Control of tree vigour and cropping is then achieved by use of a clonal interstock, such as M.26. The extensive and deep root systems of these invigorating seedling rootstocks could explain their drought tolerance, although they may also be able to extract tightly bound water from clay soils better than other more drought-sensitive rootstocks. With the current trend towards reduced use of herbicides under organic systems of production and the need to economize on water use in many areas, there may

be a strong need for a greater selection of rootstocks that are both drought-tolerant and dwarfing.

Rootstocks also adapt scions to soils infested with damaging soil pests and/or pathogens. The woolly apple aphid (*Eriosoma lanigerum* Hausmann) limits apple production significantly in many parts of the world, especially in the southern hemisphere. This pest damages apple roots most severely and in some cases can lead to tree death. Rootstock selections, such as the Malling Merton (MM) series are resistant to this pest and enable production in areas normally blighted by this pest.

Damaging pathogens, such as collar or crown rot (*Phytophthora cactorum* (Leb. and Cahn) Schroet), also limit apple production severely, especially on heavy clay or other poorly draining soils. The popular semi-vigorous rootstock MM.106 is particularly sensitive to this problem. In recent years, many apple rootstocks have been selected that show strong tolerance/resistance to this disease.

Care must be taken in selecting rootstocks so as not to increase the sensitivity of trees to other damaging pests and diseases. Use of the dwarfing and semi-dwarfing rootstocks M.9 or M.26 is not to be recommended in areas where the bacterial disease fire blight (*Erwinia amylovora* (Burr.) Winslow *et al.*) is a problem. Both of these rootstocks are particularly sensitive to this pathogen. In apple production areas where various species of mice or voles cause severe damage to the tree's root system, rootstocks such as Novole, which show some resistance to these pests, have been considered.

5.4.3 Rootstock interactions with scion cultivar and environmental conditions

The literature concerning the relative effects of different apple rootstocks on scion growth and cropping is sometimes inconsistent, leading to confusion when seeking the appropriate choice of rootstock. This is best explained by the usually subtle, but occasionally significant, interactions between the rootstocks and the scions (Tubbs, 1980) or the rootstocks and the environmental conditions (Olien *et al.*, 1991).

Usually, the relative effects of different rootstocks on the growth and cropping of the scion remain similar for the majority of scion cultivars (Hirst and Ferree, 1995). Nevertheless, the inherent vigour of the scion cultivar will greatly influence final tree size on any particular rootstock. This is why growers are advised to choose the more dwarfing sub-clones of M.9 or even M.27 rootstock for a vigorous scion cultivar such as 'Elstar', while with the less vigorous 'Cox's Orange Pippin' the more invigorating sub-clones are recommended.

The rootstock's interaction with environmental (soil and climatic) conditions are often very significant and frequently the wrong choice of rootstock or tree spacings is made. Until rootstock evaluation trials pay more attention to the prevailing environmental conditions and endeavour to understand and explain these interactions, this inconsistency of response is likely to remain an enigma. When choosing a new rootstock it is always preferable if small test plantings can be established on the site prior to any large-scale commitment to the new rootstock. Where this is not possible, it is vital to take account of the results of trials of the new rootstock that have been conducted in similar environmental conditions and with the same scion cultivar. Recent studies in the USA have attempted to use data collected from multi-site trials to estimate a 'site index' to be used in the construction of predictive models to aid rootstock selection (Olien *et al.*, 1995). To help apple growers improve their rootstock choices in the future, more research and information are needed on predicting the growth potential of sites for apple orchards.

5.5 Rootstock Mechanisms – How do Rootstocks Bring about their Many Effects on Scion Growth and Cropping?

5.5.1 Effects on vigour of growth, yields and fruit size and quality

There is still little or no understanding of how rootstocks bring about their effects on the vigour of shoot growth of scions grafted upon them. Choice of rootstock can also

affect the abundance of flowering, fruit set and yields, and the mechanisms by which these influences are brought about are also not understood. Many theories have been advanced in attempts to explain the dwarfing effect on apple scions of some rootstocks (Tubbs, 1972; Lockhard and Schneider, 1981). Some suggestions, now less fashionable, sought to explain the dwarfing effect in terms of changes in tree-water relations or nutrient uptake caused by the rootstock or its imperfect graft union with the scion (Jones, 1971, 1975). More recently, scientists have focused on studying changes in the production and movement of plant hormones within the tree brought about by use of the rootstock (Soumelidou *et al.*, 1994; Kamboj *et al.*, 1997). The hypothesis is that the rootstock, or possibly its graft union with the scion, alters the ratios and concentrations of the growth-promoting hormones, such as auxins, gibberellins or cytokinins, and maybe also the inhibiting hormones, such as abscisic acid, which are translocated within the tree. The work by Soumelidou *et al.* (1994) and Kamboj *et al.* (1997) suggested that the rates of basipetal auxin translocation were less in dwarfing than in invigorating rootstock stems. The later work also indicated that the ratios of abscisic acid to auxin content were higher in the bark of dwarfing rootstocks and that differences in cytokinin translocation rates may also be measurable (Fig. 5.2).

It is important to note that the dwarfing influence of rootstocks on apple scions is different from that achieved when using most compact scion cultivars or chemical plant-growth regulators. In comparison with invigorating rootstocks, dwarfing rootstocks/interstocks reduce the speed of extension shoot growth throughout the season and often bring about an earlier termination of this shoot extension in the late summer or early autumn. This effect and changes in tree habit towards more horizontal branch orientation (Warner, 1991) together account for the effects of the dwarfing rootstocks in reducing the size of apple-scion trees. In comparison, most compact types of scions and chemical plant-growth regulators reduce tree size by shortening the internodes of extension shoots. The full implications of these differ-

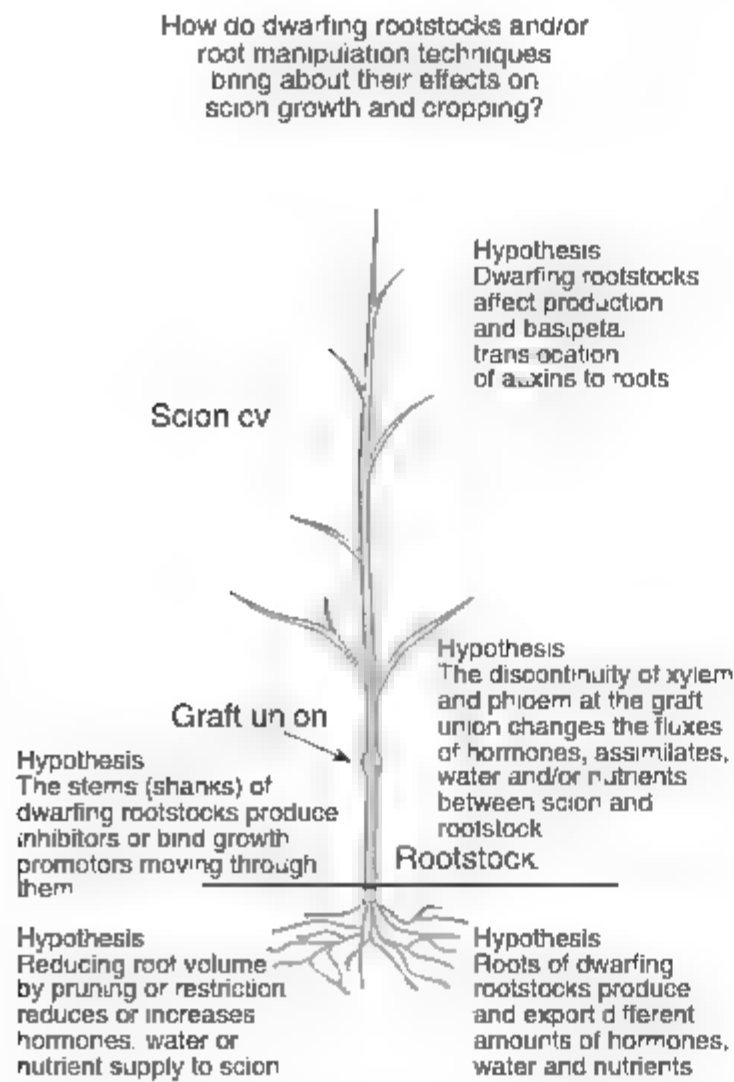


Fig. 5.2. Some hypotheses concerning how apple rootstocks bring about their dwarfing influence upon scion vigour

ences in mode of dwarfing action on tree performance and productivity have yet to be fully explored. However, short internodes and much mutual shading of leaves might be expected to have some negative effects on cropping and fruit quality in areas with less than ideal light interception. This may be one contributory reason why compact spur types of cultivars such as 'Granny Smith' (e.g. 'Granspur') often crop less efficiently than the standard non-compact parent and others, such as 'McIntosh Wijkik', are severely biennial (Fig. 5.3).

The beneficial effects of dwarfing rootstocks/interstocks on the precocity and efficiency of tree yields have often been attributed to a change in the partitioning of the dwarfed tree's assimilates from shoot growth to fruit production. However, this explanation is too simplistic, as there are several invigorating and semi-invigorating clonal rootstocks, such as M.25 and MM.106, which also induce improved yield precocity and efficiency in

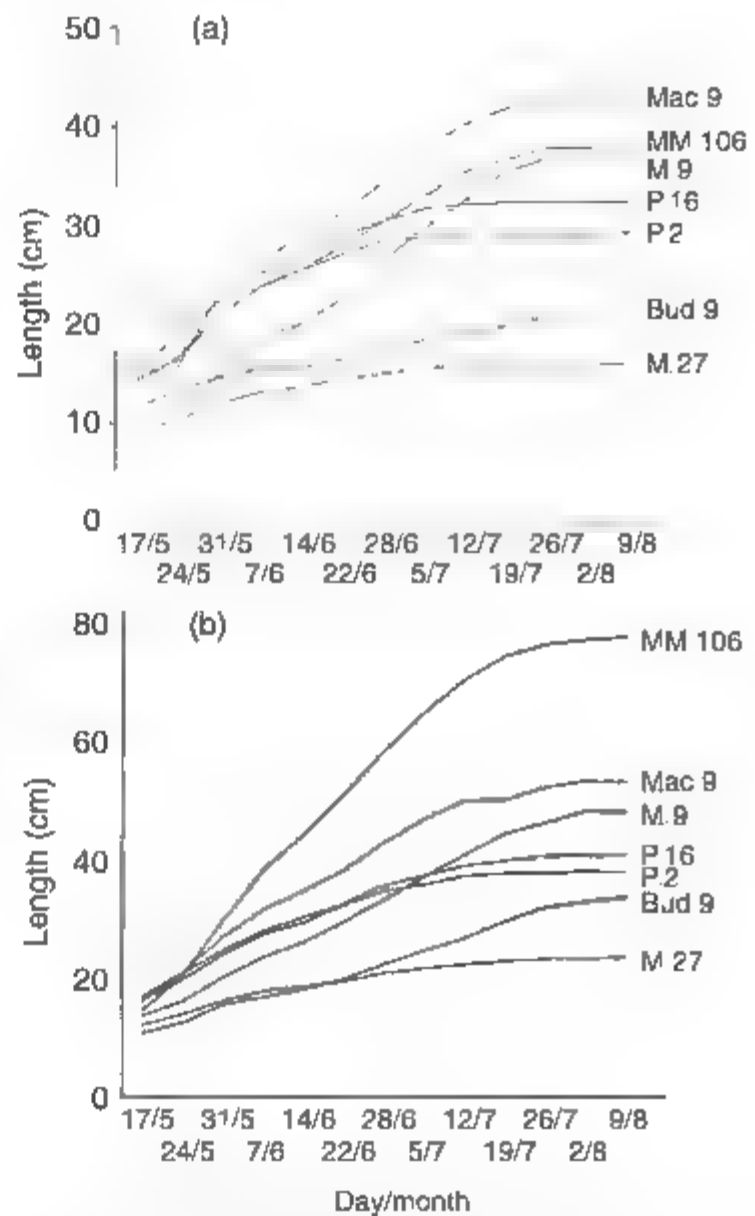


Fig. 5.3. Effect of different rootstocks on the growth of scion extends on shoots. (a) Shoots with horizontal orientation. (b) Shoots with vertical orientation

comparison with seedling rootstocks inducing the same level of scion vigour. Also, use of some interstems, which have no significant influence on tree vigour and size, may also have very beneficial effects on fruiting precocity. This is possibly explained by the high quality (size and feathering) of trees raised using an interstem rather than the interstem itself (Wertheim and Callesen, 2001).

Reducing root growth (by root pruning or root restriction) brings about dwarfing effects on scions grown on invigorating rootstocks (Schupp and Ferree, 1987; Webster *et al.*, 2000) that are similar to those brought about by use of dwarfing rootstocks. It could be argued, therefore, that the growth reduction caused by dwarfing rootstocks might be partly due to them bringing about a reduction in the root : shoot ratio of the tree. Most dwarfing clones certainly produce smaller

root systems than more invigorating rootstock clones. However, this hypothesis fails to explain the growth reduction caused by dwarfing rootstock clones when they are used as interstocks, where the dwarfing clone itself forms no roots. The dwarfing effect of using a rootstock such as M.9 or M.27 as an interstock increases with the length of interstock used up to approximately 25 cm, indicating the influence of some stem-derived dwarfing factor (Parry and Rogers, 1968). The same phenomenon is noted when scions are budded at different heights on the shanks of dwarfing apple rootstocks (Fig. 5.4); trees budded high are much more dwarfed than those budded close to ground level (Parry, 1976).

One possible explanation is that growth-inhibiting substances are formed or growth-promoting substances are broken down within the stems of dwarfing rootstock clones and that this either causes a direct effect on scion extension growth or alternatively indirectly influences scion shoot growth by effects on root growth. Much further research will be needed before the mechanisms by which dwarfing rootstocks operate are understood.

Rootstocks also influence apple-yield productivity (Rom *et al.*, 1990) but how they do this is also poorly understood. One hypothesis is that trees on dwarfing rootstocks terminate shoot growth earlier in the summer than trees on more invigorating rootstocks and thereafter partition more of their available assimilates towards the sites of floral primordia and less towards further shoot

growth. This earlier termination in growth should also result in a change in the biosynthesis and translocation of hormones from the shoot tip. The production of gibberellins and auxins in the meristems and new unfolding leaves of actively growing shoots and their translocation basipetally undoubtedly diminish once a resting bud is formed at the apex. Although a partially plausible hypothesis, it fails to explain why certain invigorating rootstocks, such as M.25, stimulate improved flowering and cropping in scions but with no reduction in tree vigour compared with trees on more poorly cropping but equally vigorous rootstocks. Whether M.25, like dwarfing rootstocks, also induces termination of shoot growth early in the season is not known. This is another area of research in need of further study.

5.5.2 Effects on tree sensitivity to environmental conditions causing severe stress

Little is understood of the mechanisms by which rootstocks differ in their resistance/tolerance to damaging pests or diseases, severe cold, drought or other unfavourable conditions. A few studies conducted recently have sought to explain the reasons for differences in apple-rootstock sensitivity to drought (e.g. Atkinson *et al.*, 1999). However, most of the rootstock effects on these parameters remain an enigma and more studies are needed in this area to aid rootstock breeding and selection in future years.

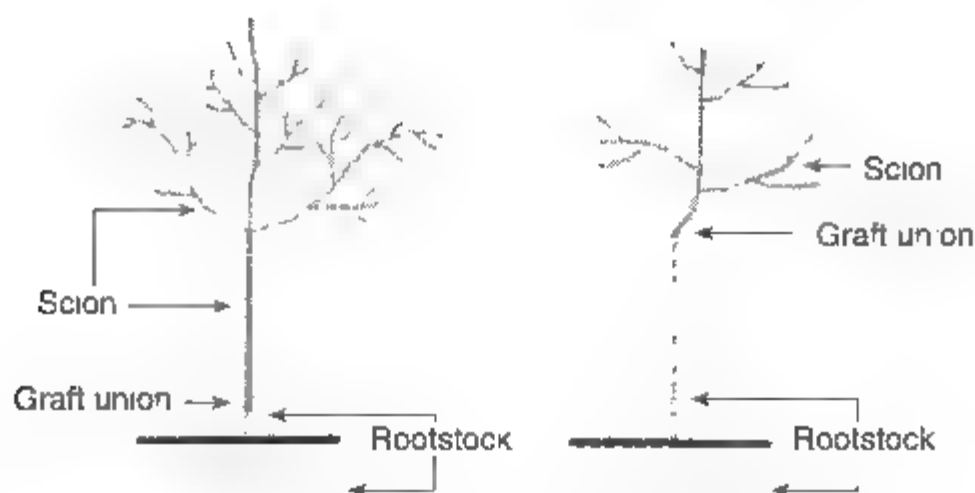


Fig. 5.4. Influence of height of budding on scion vigour.

5.6 Breeding New Apple Rootstocks

Approximately 100 years ago, all the clonal apple rootstocks used by nurserymen for raising apple trees had been selected from seedling populations and their precise origin is, for the most part, uncertain. These clones had become very mixed up by the turn of the last century and apple growers could never be certain of consistent performance when using them. A now well-documented programme of research undertaken by East Malling Research Station in England set about sorting out these mixtures and, by 1920, a series of rootstocks had been identified, described and distributed to nurseries (Hatton, 1917). Initially, nine types were released and among these type IX (Jaune de Metz or M.9) and M.7 remain popular throughout the world today. Further selections followed, but most of these proved very invigorating and most have now disappeared from commerce. Descriptions of the Malling apple-rootstock selection numbers 1 to 16 are given by Pearl (1932) and details of their effects on tree growth and cropping by Hatton (1935) and Tydeman (1955).

Following the early selection work undertaken by East Malling, there were only two rootstocks, M.9 and M.8, that could be classed as dwarfing. The second of these produced very brittle roots and trees on it were very poorly anchored. In attempts to extend the range of dwarfing rootstocks and to produce more invigorating rootstocks that exhibited good yield precocity, crosses were made using M.9 as one parent (Tydeman, 1933, 1943). The first results of orchard trials, comparing the best of these selections, were reported by Preston (1954). One extremely dwarfing selection, 3426, was never released but two other selections that showed great promise, 3436 and 3431, were eventually released as the semi-dwarfing M.26 and the very dwarfing M.27 rootstocks.

The woolly apple aphid (*E. lanigerum*) has always caused big problems to apple producers in the southern hemisphere, where it severely damages the root systems of trees. Traditionally, the resistant scion cultivar 'Northern Spy' was used as a rootstock. However, this was a very invigorating root-

stock and induced poor yield precocity and efficiency. In breeding programmes undertaken jointly by the John Innes and East Malling Institutes in the UK, resistant rootstocks, known as the Merton Immune (e.g. Merton 793) and the MM series, were developed (Tydeman, 1953). Preston (1955, 1966) described some of the initial trials using the MM rootstocks. One promising invigorating rootstock, M.25, that did not show resistance to woolly apple aphid was also released from this breeding programme.

The popular rootstocks from the original selections (M.7 and M.9) together with the subsequent releases of M.26, M.27 and Merton 793 and the MM series, provided fruit growers in many parts of the world with reliable rootstocks offering a range of scion vigour control. However, these rootstocks are not suited to all areas of apple production. M.9 and M.27 are sensitive and very sensitive to winter cold injury, respectively, and fruit-breeding programmes have been initiated in many parts of the world to produce dwarfing rootstocks exhibiting improved cold tolerance. This focus on cold tolerance in apple-rootstock breeding has been and remains of particular importance in the programmes conducted in eastern and central Europe. Details of breeding programmes in Poland, Belarus, the Ukraine, Russia, the Czech Republic and the Baltic states are given in Sadowski and Hrotko (1999). Breeding for cold tolerance has also been a prime objective of programmes in Canada (Quamme, 1990; Elfving *et al.*, 1993; Quamme *et al.*, 1999) and the USA (Cummins and Aldwinckle, 1995). Usually cold-tolerant cultivars, such as 'Antonovka', or hardy crab apples or the cold resistant rootstock A2 have been used in crosses with M.9 or M.8.

Other problems became evident with the existing range of rootstocks. Many, including M.9 and M.26, are very sensitive to fire blight attacks, while MM.106 is very susceptible to collar (crown) rot and both MM.106 and M.26 are sensitive to tomato ringspot virus. Also, despite the success of the MM series of rootstocks against woolly apple aphid, none of this series is dwarfing. In a comprehensive programme of breeding, scientists at Cornell University in the USA have sought to over-

come these and other problems and produce new improved clones of rootstocks for apples (Cummins and Aldwinckle, 1995; Johnson, 1999; Robinson *et al.*, 1999). Although showing initial promise, most of these Geneva, New York, selections have yet to be fully tested in different parts of the world.

It is important that scientists and others involved in breeding rootstocks take note of the changing requirements of apple producers throughout the world. As chemical soil fumigants are withdrawn from use and as organic systems of production (under which weed competition may increase) become more popular, there will be a growing need for dwarfing rootstocks that are more able to tolerate replant problems and drought stress.

All new rootstocks have, until recently, been produced using conventional techniques of breeding. In most cases existing rootstocks, such as M.9, have been crossed with other rootstocks, scion cultivars or *Malus* species and the siblings screened for the desired characteristics. In the future, novel techniques of fruit breeding, which use new methods of molecular biology, may play a greater role in producing new rootstocks. Already, genes derived from the cecropin moth have been introduced into M.26 and M.9 rootstocks, in attempts to impart fire blight resistance into these susceptible clones (H. Aldwinckle, Geneva, New York State, 2000, personal communication). Similarly, *rol* genes have been used in other work in attempts to improve rooting and dwarfing characteristics of rootstocks (Welander, 1998; Welander and Zhu, 2000). This research is still at an early stage and it is not yet known how consistent the expression of the introduced characteristics will be once trees are raised on the transgenic rootstock clones and planted in the orchard. In Europe, it is also possible that fruits raised on trees propagated on transgenic rootstocks may prove unacceptable to consumers.

5.7 Choosing the Appropriate Apple Rootstock

A very large range of rootstocks, either seedling or clonal, is now available for use by nurserymen and fruit growers. It is vital that

the correct choice is made to suit the environmental conditions, the economic constraints and the management strategies of the particular apple-production enterprise. Choice of the appropriate rootstock can, in certain circumstances, make the difference between profitability and loss of the apple orchard. Unfortunately, rootstock decisions made by growers are not always as objective and rational as they might be. The current fashion for the use of a particular rootstock in another area of the world, poor or biased advice from extension specialists or simply pressure to sell by nurseries may all lead to the wrong choice being made. In choosing the appropriate rootstock it is essential to list and rank the priorities needed, based on the environmental and other constraints relevant to the fruit enterprise and the chosen site for the orchard.

The current fashion in many parts of the world is to grow apple trees on dwarfing rootstocks, such as M.9. The trees are dwarf in stature and hence easier and cheaper to manage and harvest than larger trees. Trees on M.9 crop precociously and abundantly and produce fruits of large size. The dwarfed trees also have environmental advantages in that they can be targeted with agrochemical sprays very accurately, so greatly reducing spray drift into the surrounding atmosphere. Considering these advantages, it is easy to appreciate why M.9 has become so popular throughout the world and why many growers might consider no other rootstock when planning their new orchard. Nevertheless, like all other rootstocks, M.9 has several critical disadvantages. First, it is very sensitive to damage to its root system by the woolly apple aphid (*E. lanigerum*), which has, in the past, proved a constraint on production in many southern hemisphere countries. It is also very sensitive to fire blight and orchards grafted on to it in the eastern states of the USA have recently suffered huge tree losses as a result of this disease. In addition, M.9, like most other dwarfing rootstocks, is sensitive to winter cold injury, particularly on poorly drained soils, making its use in eastern and central Europe, parts of Canada and the USA very risky. It is also poorly anchored, needing expensive stakes or other means of support in all situations, and it also

tolerates hot, dry soils very poorly. Where land and labour costs are relatively inexpensive but the costs of nursery trees are high, it may be advantageous, economically, to choose a more invigorating rootstock than M.9. A similar choice may be appropriate on soils of lower-than-average fertility or where water supplies are very limited on sites subject to transient drought. On sites such as these, M.9 and most other dwarfing rootstocks are inappropriate choices.

The above brief points are made as an example to emphasize the importance of careful ranking of priorities when choosing an apple rootstock.

5.7.1 Attributes of the ideal rootstock

There are certain attributes common to all good clonal (vegetatively propagated) rootstocks. The essential attributes for all rootstocks are:

- Long-term graft compatibility with the scion. No grower can tolerate delayed incompatibility occurring in the orchard and premature tree death. Fortunately, graft incompatibility is only occasionally a problem with apples, usually when trees are grafted on to species or hybrids of crab apples.
- Good health. Rootstocks used for raising apple trees should be free from damaging pests and diseases. Of particular importance is freedom from virus and bacterial diseases. Virus-infected rootstocks will transmit the disease to any scions budded or grafted on to them and usually this will result in reduced growth, yield and fruit quality. It is vitally important that rootstocks guaranteed free from viruses are chosen. The bacterial disease crown gall (*Agrobacterium tumefaciens* (Smith and Townsend) Conn.) reduces scion-tree growth on some soil types and most health-certification schemes demand freedom from this pathogen. Fire blight is also damaging and rootstocks should be tested and guaranteed free of this bacterial pathogen. Most countries offer schemes whereby rootstocks are certified as

healthy. More information on the diseases affecting apple rootstocks and scions is contained in Chapter 18

The other desirable rootstock attributes are shown below. How these are ranked in order of priority will depend largely on the specific needs of the nurseryman or fruit grower and the particular constraints affecting his or her tree or fruit production.

5.7.1.1 Attributes important to the nurseryman

- Ease of propagation. Rootstocks that are difficult to propagate are unpopular with nurserymen and result in trees that are very expensive to produce. All rootstocks should be easy to propagate from seed or from layering or cutting techniques.
- Good performance in the nursery. The ideal rootstock should establish well in the liner nursery, exhibit good bud or graft compatibility with the scion and produce well-feathered trees.

5.7.1.2 Attributes important to the fruit producer

- Ability to control scion vigour to the required level. The chosen rootstock should be capable of controlling the vigour of the scion trees to the level required by the grower. This will be influenced by the environmental conditions in the orchard and by the management system adopted by the grower.
- Ability to induce precocious and abundant cropping. The ideal rootstock should induce scions to flower and crop significantly in the first few years following planting, if rapid returns on orchard investments are to be achieved. The rootstock should also induce consistent and abundant cropping of large high-quality fruits.
- Resistance/tolerance to biotic stress factors. Many sites chosen for apple production are infested with damaging pests or diseases. It is essential that these problems are recognized prior to orchard establishment and rootstocks chosen to provide resistance/tolerance to the problems.

- Tolerance to abiotic stress factors. Where sites suffer from transient drought or asphyxiation of the soil, rootstocks should be chosen to provide some tolerance of these conditions. Where severe winter cold is a problem rootstocks with cold tolerance are essential.
- Freedom from suckering. Rootstocks that produce many suckers, either from their shanks or from their root systems, are a problem to the fruit grower. The suckers inhibit weed control practices, increase chances of pest and disease infection, compete with the tree and are expensive to remove annually.

5.8 Apple Rootstocks Propagated from Seed

Fruit growers in very few countries now rely on apple rootstocks raised from seed. Only in countries where clonal propagation of rootstocks has proved too difficult or uneconomic are seedling rootstocks still used to any significant extent. Seedling rootstocks, mainly of the scion cultivar 'Red Delicious', were used quite extensively in the USA until relatively recently. Their main use was for raising trees of compact- or spur-type scion clones, where control of tree vigour by use of a dwarfing rootstock was not a priority. More recently, this use has been superseded by the use of semi-invigo-

rating clonal rootstocks for raising these compact scion types.

Apple rootstocks are still raised from seed quite extensively in China, where *M. sieversii* and *M. prunifolia* are popular choices. These seedling types are reported to give deep rooting and good drought tolerance, as well as tolerance to severe winter-cold conditions. Japanese growers have traditionally used seedling-raised rootstocks, although this practice has begun to change in recent years with the use of M.26 interstocks and the development of clonal dwarfing rootstocks. More recently, Chinese growers have begun to use M.26 as an interstock to provide some degree of scion growth control when using invigorating seedling-raised rootstocks of *M. prunifolia* or *M. sieversii*.

5.9 Vegetatively Propagated Rootstock Clones and Sub-clones Used to Control Tree Vigour

Most apple-scion cultivars grown on their own roots or on seedling rootstocks produce large standard trees of 7–10 m in height and spread. Whilst such trees are acceptable in countries where land and labour are very inexpensive, in most apple-producing areas of the world some reduction in this natural vigour is desired. Clonal apple rootstocks have been available for many years, which offer a full range of scion-vigour control (Fig. 5.5).

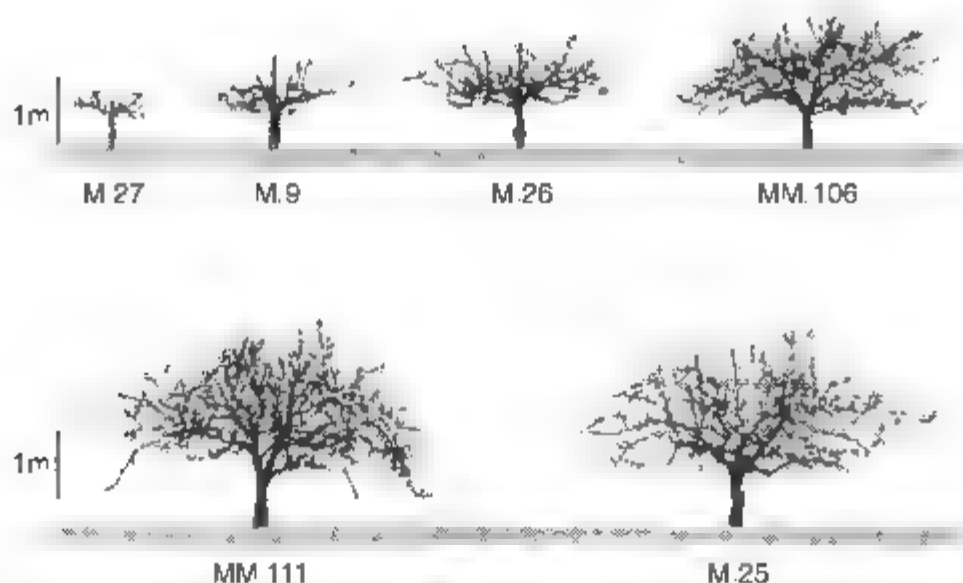


Fig. 5.5. Silhouettes of 'Cox's Orange Pippin' apple-trees grafted on a range of Malling and Malling–Merton rootstocks, showing their effect on scion vigour control

Rootstocks providing vigour control similar to that of M.27 are often referred to as super dwarfing and those similar to M.9 as dwarfing. Similarly, rootstocks with vigour similar to M.26 are classed as semi-dwarfing and those similar to MM.106 as semi-vigorous. The vigorous rootstocks are those similar to M.25 or to seedlings. In recent years, these rootstock vigour categories have become indistinct, as many new rootstocks exhibiting vigour intermediate between the main categories have been selected. Nevertheless, an attempt is made below to list and categorize some of the many rootstocks available for apple.

5.9.1 Super dwarfing selections

The most dwarfing rootstock, which has been available from commercial nurseries for many years, is the super dwarfing selection M.27. When grafted with most scion cultivars this rootstock produces trees that are 2.5 m or less in height and spread. Although of great value to fruit growers wishing to establish very high-density planting systems, it is unsuited to many soils and sites. Trees on M.27 have relatively shallow root systems and are not suited to poor, infertile, shallow or droughty soils. The rootstock induces heavy fruit set and, unless fruitlets are thinned severely, fruit sizes will be smaller than for trees on M.9. One of the disadvantages listed above for M.27 (i.e. sensitivity to drought and associated small fruit size) is also associated with several other rootstocks more recently released in the same vigour category. Trials at Horticulture Research International (HRI)-East Malling have shown that trees on B.146 and P.22 are extremely dwarfing and produce very poor fruit size when grown without supplementary irrigation (Webster and Hollands, 1999a), even in the relatively moist climatic conditions of the UK. However, on irrigated and highly fertile soils, such as those found in The Netherlands, both of these rootstocks perform better than M.27.

M.27 and other newer rootstocks of similar vigour (see Table 5.1) are best used for vigorous (e.g. triploid) scion varieties

planted in high-density planting systems on deep, highly fertile soils with adequate supplies of water (Plate 5.1). Other new rootstocks showing preliminary promise in this vigour category are AR.10-2-5, AR.628-2 and AR.69-7 from the HRI-East Malling breeding programme (Webster and Tobutt, 2001).

5.9.2 Dwarfing selections

5.9.2.1 M.9 and its 'sub-clones'

The tree vigour currently preferred by most apple producers is that epitomized by trees on M.9. The final size of trees grown on M.9 will depend greatly on the inherent vigour of the scion cultivar, the soil fertility and the management system adopted by the grower. However, the aim in many parts of northern Europe is to grow trees that are no more than 3 m in height, so that all pruning and harvesting can be achieved without using ladders (Plate 5.2). Where light levels are very good, trees on M.9 are often grown somewhat taller (as in the central axe system of training) but, although yields are increased using such systems, so also are the costs of management if more work using ladders or driven platforms becomes necessary.

Compared with many of the other popular clonal rootstocks for apple (e.g. M.26 and MM.106), M.9 is rather less productive on the nursery layer bed. This proved a particular problem with M.9A, the first selection of M.9 produced free from major viruses. Although M.9 EMLA, the first selection produced free of all known major and latent viruses, was easier than M.9A to propagate, many nurserymen still felt that improved propagation was an important goal. As a consequence, nurserymen and researchers based in Belgium, The Netherlands, Germany and France began to reselect from within layer beds of M.9, with the objective of identifying new 'sub-clones' of M.9 that exhibited better propagation characteristics. Several sub-clones are now marketed, especially in Europe, and it is often difficult for the fruit producer to determine which one to choose, as the evidence from trials comparing these sub-clones is sometimes inconsistent.

Table 5.1. Some traditional and more recently released super dwarfing rootstocks for apples

Rootstock	Origin	Parents	Availability of rootstock (2001)	Remarks	References
M.27	HRI-East Malling, UK	M.13 × M.9	Widely available	Super dwarfing; induces good precocity and high yield efficiency; may induce small fruit size; poorly anchored, sensitive to winter cold, drought and woolly apple aphid	Preston, 1954, 1971; Barritt <i>et al.</i> , 1995
B.146	Michurinsk College, Russia	Not known	Unavailable for commercial plantings	Vigour variable depending upon soil type and irrigation (M.27 to M.26); good yield efficiency; brittle roots; bad burr-knots and suckering; winter-hardy; red leaves	Zagaja <i>et al.</i> , 1988; Wertheim, 1991; Barritt <i>et al.</i> , 1995
B.491	Michurinsk College, Russia	Not known	Unavailable for commercial plantings	Vigour similar to M.27; good yield efficiency; winter-hardy; high uptake of calcium into leaves and fruits; easy to propagate	Wertheim, 1991; Callesen, 1997
BM.427	Balsgård, Sweden	M.4 × 'Antonovka Kamenskaya'	Limited availability for commercial plantings	High yield efficiency; winter-hardy; otherwise similar to M.27; very limited trials/information available currently	Trajkovski and Andersson, 1980
G.65	Cornell University, New York, USA	M.27 × 'Beauty' crab apple	Temporarily unavailable	Similar or less vigour than M.27; growth too weak in most situations; high yield precocity and efficiency; suckers; moderately resistant to fire blight and collar rot	Robinson <i>et al.</i> , 1999
JM.1, 5 and 8	Apple Research Centre, NIFTS, Japan	'Marubakado' × M.9	Experimental rootstocks, still under evaluation	Preliminary evidence from Japan suggests vigour similar to M.27; enhanced fruit firmness and sugar content; resistant to collar rot; very limited trials/information available currently	Bessho and Soejima, 1992; Soejima <i>et al.</i> , 1998
J-TE-G	Techobuzice, Czech Republic	M.9 × 'Croncels'	Available in Europe	Similar vigour to M.27; very high yield efficiency; in other respects similar to M.27	Dvorák, 1988
M.20	HRI-East Malling, UK	Chance seedling	Limited availability in the UK, The Netherlands and Canada	Similar vigour to M.27; good yield precocity and efficiency; induces better fruit size than M.27; poor anchorage; suckers more than M.27; difficult to propagate	Jackson, 1986; Wertheim, 1992

P.22 ('Last Minute')	Skerniewice, Poland	M.9 × 'Antonovka'	Widely available	Much more invigorating than M.27 if planted on fertile soils with adequate supplies of water; on drier soils tree size very much reduced; three sub-clones – J and K (more juvenile) and S (more adult) – available in Europe; high yield precocity and efficiency; anchorage similar to M.27, some suckering; winter-hardy; sensitive to drought and to woolly apple aphid, tolerant to collar rot	Zagaja, 1980; Barritt <i>et al.</i> , 1995; Kruczynska and Czynczyk, 1998; Webster and Hollands, 1999a; Czynczyk and Piskor, 2000
P.59 ('Polan 59')	Skerniewice, Poland	A.2 × B.9	Limited availability in Europe	Similar vigour to P.22 in Polish trials; good yield efficiency; red leaves; very limited trials/information available currently	Jakubowski, 1999a,b
P.61	Skerniewice, Poland	P.16 × M.26	Unavailable for commercial plantings	Very dwarfing, less than P.22 in Polish trials; very high yield efficiency; very limited trials/information available currently	Jakubowski, 1999a,b
P.66	Skerniewice, Poland	P.22 × M.26	Unavailable for commercial plantings	Vigour greater than P.61 but significantly less than M.9; good yield efficiency; very limited trials/information available currently	Jakubowski, 1999a,b
V.3	Vineand, Canada	'Kerr' crab apple open-pollinated	Limited availability for trials in the USA and Europe	Variable vigour between P.22 and M.9; high yield efficiency; winter-hardy; limited trials/information to date	Elfving <i>et al.</i> , 1993; Barritt <i>et al.</i> , 1995
Vomesti 2	Vomesti, Romania	M.9 × 'Cretesc'	Currently available only in country of origin	Vigour similar to M.27 or P.22 in Dutch trials; good yield efficiency; very limited trials/information available currently	Parnia <i>et al.</i> , 1997

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It is generally accepted that most of these new sub-clones of M 9 are easier to propagate than the traditional virus-free M.9 EMLA sub-clone. Although all are similar genetically, there are ontogenetic differences between the sub-clones. The more adventitious (often wrongly called juvenile) types usually have slightly narrower leaves, branch more freely and are easier to propagate, whereas the less adventitious (or more adult) types show the opposite characteristics (Van Oosten, 1986). Trials at East Malling conducted some years ago (Webster and Jones, 1989) showed that propagation of the EMLA sub-clone of M.9 could also be improved if it was put through an extended *in vitro* phase prior to establishing hedges or stool beds. Repeated subculturing in micropropagation induced a form of adventitiousness or false juvenility, which persisted for many years after establishment in the nursery if the hedges/stools were severely pruned each year.

The comparative attributes of the various M.9 sub-clones when used for fruit produc-

tion in the orchard have been studied in several countries and the results are slightly variable (Wertheim, 1997; Webster and Hollands, 1999b). Small differences in tree vigour are noted, with the Dutch sub-clone Fleuren 56 currently the most dwarfing and the Belgian sub-clone K (Nicolai) 29 among the more invigorating. However, the differences between the most dwarfing and invigorating clones are rarely more than 15%. Trials in the UK testing most of the sub-clones have shown no significant differences in their effects on scion yield precocity and efficiency if trees of similar size and branching are planted (Webster and Hollands, 1999b). Growers wishing to use M.9 should choose the more invigorating sub-clones, where the site and soils are slightly suboptimal or where a weak scion cultivar is chosen and planted at medium tree densities. Where soils are highly fertile, scions have strong inherent vigour and very high-density planting systems are chosen, the weaker sub-clones should be chosen. Table 5.2 lists a few of the more popular sub-clones of M 9

Table 5.2. 'Sub-clones' of M 9 available as virus-free rootstocks

Name or number of sub-clone	Origin	Remarks
M 9 A	UK	The first sub-clone freed of major viruses; a poor clone in the nursery
M 9 EMLA	UK	The first M 9 sub-clone freed of all known major and latent viruses; moderate vigour; less easy to propagate than many sub-clones
Burgmer 719 (= B 1)	Germany	Slightly more invigorating than the EMLA sub-clone in UK trials
Burgmer 751 (= B 2)	Germany	Slightly more invigorating than the EMLA sub-clone in UK trials
Burgmer 984 (= B 3)	Germany	Slightly more invigorating than the EMLA sub-clone in UK trials
Fleuren 56	The Netherlands	Selected by the Fleuren nursery; the least vigorous sub-clone known currently
NAKB T 337	The Netherlands	The most often used of the four virus-free sub-clones produced by NAKB
K (Nicolai) 29 (RN 29)	Belgium	One of the more invigorating 'sub-clones' of M 9
Pa'am 1 (Lancep)	France	Easier to propagate and slightly less vigorous than M 9-EMLA
Pa'am 2 (Cepiland)	France	Similar or slightly more vigorous than M 9-EMLA; easier to propagate

5.9.2.2 Alternatives to M.9 as dwarfing rootstocks

Breeders of apple rootstocks have tried, over the last 40 years, to produce rootstocks with similar vigour and attributes to M.9 but which have additional advantages. Particular goals have been improved resistance to winter-cold damage (see Russian, Polish and Canadian rootstock selections) and to fire blight (see Geneva, New York State, rootstock selections). Although several new rootstocks exhibiting increased resistances to these and other problems have been produced, some of them are, unfortunately, slightly inferior to M.9 in one or more other characteristics (e.g. yield efficiency, drought tolerance, fruit size, etc.).

Mark (previously MAC.9), a rootstock bred at Michigan State University in the USA, showed great promise initially as a rootstock with vigour between M.9 and M.26 that induced excellent yield precocity and efficiency (Carlson and Perry, 1986; Perry, 1990). Unfortunately, it has performed very poorly in some trials, especially those planted on hot dry soils. It is very sensitive to drought (Fernandez *et al.*, 1997) and to crown gall and develops a swelling at or just below ground level, which reduces tree performance on some sites (Stover and Walsh, 1994) and increases tree-to-tree variability in the orchard.

Most of the other rootstocks produced and released with vigour similar to M.9 have been bred to provide improved tolerance to winter-cold injury and should be chosen in preference to M.9 in areas where very low winter temperatures are common. However, as can be noted in Table 5.3, some of these selections are inferior to M.9 in one or more of their other attributes and care must be taken when choosing among them. Like M.9, these rootstocks generally require staking.

Other rootstocks in this vigour category that are showing initial promise in experimental trials are AR.680-2, AR.295-6 and AR.486-1 from the HRI-East Malling programme and G.16 and CG41 from the Cornell Geneva programme.

5.9.3 Semi-dwarfing selections

Where climatic and soil conditions are unsuited to use of M.9, apple growers requiring dwarfed trees often turn to slightly more invigorating clonal rootstocks such as M.26 or other rootstocks of similar vigour potential, which induce 15–30% more vigour and tree size than M.9 (Plate 5.3). M.26 exhibits much better tolerance of winter cold than M.9 (Ferree and Carlson, 1987) and for this reason has often been chosen for areas where winters are occasionally severe. It is also frequently used as a dwarfing interstock (see below) in countries such as Japan and China. Like M.9, trees on M.26 need stakes or other supports in all but the most sheltered locations.

Although a useful rootstock when used in appropriate situations, M.26 does have several disadvantages. It has a tendency to produce many burr-knots on the above-ground rootstock stem (shank) and these can prove to be sites for entry of damaging pests and pathogens. Excessive burr-knotting also reduces growth on the scion and this can result in uneven growth in orchards planted on M.26. This is especially severe where trees are machine-planted with differing amounts of rootstock shank exposed above ground level. Growers choosing M.26 should plant the trees with their graft unions as close as possible to the soil surface, without causing scion rooting; this should greatly reduce the problems of burr-knotting and uneven tree growth. Although sub-clones of M.26 exhibiting less burr-knotting have been selected in The Netherlands (Denissen *et al.*, 1993; Wertheim and Kunneman, 1993), these have yet to gain widespread popularity elsewhere.

There are also a few reports of scions on M.26 rootstock being less efficient in calcium uptake than trees on M.9 and other rootstocks. Whilst unlikely to be a problem with cultivars efficient in calcium uptake (e.g. 'Gala'), M.26 is not the best choice for cultivars such as 'Cox's Orange Pippin', where calcium-related disorders, such as bitter pit, can prove problematic. M.26 is also very sensitive to fire blight and fruit breeders based at Cornell University in the USA are currently developing transgenic

Table 5.3. Some of the traditional and new dwarfing rootstock selections for apples.

Rootstock name or number	Origin	Parents (if known)	Availability (2001)	Remarks	References
M.9 ('Jaune de Metz')	Reselected at HRI-East Mailing, UK	Chance seedling found in France	Widely available	The most popular dwarfing rootstock; induces excellent yield precocity and efficiency; induces large fruit size, brittle roots; poor anchorage, some suckering, depending upon scion cultivar, rootstock sub-clone and site conditions; sensitive to winter cold, poor drainage and shows some drought sensitivity; sensitive to fire blight and to woolly apple aphid; some resistance to collar rot	Hatton, 1917; Van Oosten, 1977, 1986; Webster and Hollands, 1999b
B.9	Michurinsk College, Russia	M.8 × 'Red Standard'	Available	Vigour between M.9 and M.26; good yield efficiency; anchorage slightly better than M.9; winter-hardy; sensitive to woolly apple aphid, resistant to collar rot; propagation difficult; red leaves; exhibited more field tolerance to fire blight infections than M.9	Barritt <i>et al.</i> , 1995; Kruczynska and Czynczyk, 1998; Webster and Hollands, 1999a
B.469	Michurinsk College, Russia	Not known	Experimental rootstock, still under evaluation	Vigour similar to M.9; induces good yield and fruit size; winter-hardy; very limited trials/information available currently	Wertheim, 1991
C.6	Louisiana, USA	M.8 open-pollinated	Unavailable commercially in Europe	Variable vigour M.9 to M.26; precocity, yield efficiency and fruit size variable but mainly similar to M.9; very limited trials/information available currently	Barritt <i>et al.</i> , 1995
G.16	Cornell University, New York, USA	Ottawa 3 × <i>Malus floribunda</i>	Limited availability in USA and Europe	Similar vigour to M.9; good yield efficiency; resistant to fire blight and collar rot; very limited trials/information available currently	Johnson, 1999; Robinson <i>et al.</i> , 1999
JM.2	Apple Research Centre, NIFTS, Japan	'Marubakado' × M.9	Experimental rootstocks, still under evaluation	Vigour similar to M.9 in Japanese trials; tolerant of woolly apple aphid; resistant to collar rot; easy propagation from hardwood cuttings; very limited trials/information available currently	Bessho and Soejima, 1992
JM.7	Apple Research Centre, NIFTS, Japan	'Marubakado' × M.9	Experimental rootstocks, still under evaluation	Vigour similar to M.9 in Japanese trials; tolerant of woolly apple aphid; resistant to collar rot; easy propagation from hardwood cuttings; very limited trials/information available currently	Bessho and Soejima, 1992

J-OH-A	Omomouc-Holice, Czech Republic	Not known	Limited availability in Europe	Vigour slightly greater than M 9; high yield efficiency; anchorage similar to M 9; possible virus sensitivity; very limited trials/information available currently	Dvorak, 1983, Mantinger, 1996
Jork (J)-9	Jork Institute, Germany	M.9 open-pollinated	Available in Europe	Vigour similar to or slightly more than M 9; good yield efficiency and fruit size; some burr-knots and suckers; more hardy than M.9; tolerates soil/ environmental stresses well; resistant to collar rot; easy to propagate	Faby <i>et al.</i> , 1986; Wertheim, 1991
J-TE-E	Techobuzice, Czech Republic	Not known	Limited availability in Europe	Vigour similar to M 9; high yield efficiency; anchorage similar to M 9; possible virus sensitivity; very limited trials/information available currently	Dvorák, 1988
J-TE-F	Techobuzice, Czech Republic	Not known	Limited availability in Europe	Vigour similar to M 9; medium to high yield efficiency; anchorage similar to M 9; possible virus sensitivity; very limited trials/information available currently	Dvorák, 1988
M.8 ('Clark Dwarf')	Reselected at HRI- East Malling, UK	Originally known as 'French Paradise'	Available in genetic collections	Vigour similar to M 9; good yield efficiency; very poor anchorage due to brittle roots; suckers more than M 9; sensitive to poor drainage and drought; sensitive to woolly apple aphid	Hatton, 1917; Brase, 1954
MAC 9 (Mark)	Michigan State University, USA	M.9 open-pollinated	Limited availability	Vigour variable depending upon soil type; usually between M.9 and M.26; very good yield efficiency; anchorage slightly better than M 9; swellings at soil line; drought-sensitive and poor performance in hot dry soils; more resistant to collar rot than M.9; weak union, with some triploid scions	Carlson, 1980; Perry, 1990; Barritt <i>et al.</i> , 1995; Webster and Hollands, 1999a
MAC. 39 Ottawa 3	Michigan State University, USA Ottawa, Canada	M.9 open-pollinated 'Rob'n' x M.9	Not available commercially Limited availability	Vigour slightly less than M 9; suckers badly; very limited trials/information available currently Vigour similar to M 9; good yield productivity; anchorage similar to M 9; winter-cold-tolerant; very sensitive to virus; resistant to collar rot; sensitive to woolly apple aphid; very difficult to propagate by conventional techniques	Carlson, 1980; Barritt <i>et al.</i> , 1995 Granger, 1984; Quamme and Brownlee, 1990; Barritt <i>et al.</i> , 1995
P.2 ('Skilg')	Skerniewice, Poland	M.9 x 'Antonovka'	Available in Europe	On fertile soils vigour similar to M 9; but it suffers from transient drought; tree size is much smaller; good yield productivity; fruit size poor unless irrigated sufficiently; anchorage similar to M.9, suckers slightly; winter-hardy; sensitive to woolly aphid; resistant to collar rot	Zagaja, 1980; Barritt <i>et al.</i> , 1995, Kruczynska and Czynczyk, 1998; Webster and Hollands, 1999a

Continued

Table 5.3. Continued.

Rootstock name or number	Origin	Parents (if known)	Availability (2001)	Remarks	References
P 16 ('Lizzy')	Skerniewice, Poland	'Longfield' × M 11	Available	Vigour very variable, depending upon soil conditions; on fertile soils equal to M 9, on poorer soils similar to M.27; very yield-efficient; fruit size usually less than on M.9; anchorage similar to M.9; may sucker profusely on some sites; hardiness similar to M 9; sensitive to woolly aphid; resistant to collar rot	Zagaja, 1980; Barritt <i>et al.</i> , 1995, Kruczynska and Czynczyk, 1998; Webster and Hollands, 1999a
P 60 ('Polan 60')	Skerniewice, Poland	A.2 × B.9	Available in Europe	Similar vigour to P.2; good yield efficiency; suffers from burr-knotting and superficial rooting; winter-hardy; red leaves; very limited trials/information available currently	Zagaja <i>et al.</i> , 1991; Jakubowski, 1999a,b; Kurlus and Ugolik, 1999
P 62	Skerniewice, Poland	A.2 × M 27	Currently available only for trials	Vigour slightly less than for M 9 in Polish trials; very high yield efficiency; very limited trials/information available currently	Jakubowski, 1999a,b
P 67	Skerniewice, Poland	A.2 × P.2	Currently available only for trials	Vigour similar to M 9 in Polish trials, very high yield efficiency; very limited trials/information available currently	Jakubowski, 1999a,b
'Supporter 1'	Dresden, Germany	M.9 × <i>Malus baccata</i>	Increasing availability	Vigour 20% less than M 9; high yield efficiency; similar hardiness to M 9; as yet minimal evidence available from trials in countries other than Germany	Fischer, 1997, 1999
'Supporter 2'	Dresden, Germany	M.9 × <i>Malus</i> × <i>micromalus</i>	Increasing availability	Vigour 15% less vigorous than M 9; high yield efficiency; hardy; almost no evidence yet available from trials in countries other than Germany	Fischer, 1997, 1999
'Supporter 3'	Dresden, Germany	M.9 × <i>Malus</i> × <i>micromalus</i>	Increasing availability	Vigour similar to M 9; high yield efficiency; hardy; almost no evidence yet available from trials in countries other than Germany	Fischer, 1997, 1999
V.1	Vineand, Canada	'Kerr' crab apple open-pollinated	Experimental; still under evaluation	Slightly more invigorating than M 9; similar yield efficiency; winter-hardy; very limited trials/information available currently	Elfving <i>et al.</i> , 1993; Barritt <i>et al.</i> , 1995

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sub-clones of M.26 that have genes introduced that are aimed at providing increased resistance to this damaging pathogen.

Fruit breeders have endeavoured to produce new rootstock clones with similar vigour and cold tolerance to M.26 but with no burr-knotting and improved induction of yield precocity and efficiency. A few of these are listed in Table 5.4.

Other experimental rootstocks showing promise in this vigour category but which have yet received only limited evaluation are AR 801-11 from the HRI-East Malling programme and several selections from the Geneva programme.

5.9.4 Semi-vigorous to vigorous selections

Although most orchards of 50 or more years ago were planted on semi-vigorous or vigorous rootstocks, these have become much less popular in recent times (Plate 5.4). They are still used for dessert-apple plantings on very poor soils where dwarfing rootstocks will not thrive. Also, they are still very popular with producers of apples grown for the apple-juice or cider markets. Cider-apple trees are harvested using mechanical shakers and the fruits are mechanically collected up from the orchard floor. Most dwarfing rootstocks are unsuited to mechanical shaking, on account of their shallow and often brittle root systems.

For many years the two most popular semi-dwarfing rootstocks have been M.7 and MM.106. M.7 is popular in the USA on account of its good adaptability to different soil types, its induction of good precocity and yield efficiency and its resistance to collar rot and fire blight. However, it suckers and is susceptible to winter injury and trials in Europe have shown it to be less productive than MM.106. This latter stock induces excellent yield precocity and productivity but is sensitive to collar and crown rots as well as fire blight. Recently, several rootstocks have been tested from within the Cornell Geneva rootstock-breeding programme that have shown early promise. Several exhibit resistance to fire blight, collar rot and woolly apple aphid. In addition several rootstocks selected from the HRI-East

Malling programme have performed well in trials in the UK and New Zealand. AR.86-1-25 (soon to be named M.116) and AR.86-1-20 have produced trees similar in growth and yields to trees on MM.106, but with much improved resistance to collar rot. Some of the traditional and/or currently popular semi-invigorating and invigorating apple rootstocks are listed and described in Table 5.5

5.9.5 Very vigorous selections

There is nowadays little demand for vigorous clonal rootstocks for apple cultivation. Many of the early selections, such as M.1, M.2, M.12, M.16 and Crab C, have disappeared from commerce. Only Merton 793 remains a popular rootstock, especially in the southern hemisphere. Table 5.6 lists a few of the invigorating rootstock clones.

5.10 Clonal Rootstocks Used to Adapt Trees to Unfavourable Environmental Conditions

5.10.1 Tolerance to winter-cold injury

Several of the traditional and most popular rootstocks, such as M.9 and M.27, exhibit poor tolerance to severe winter cold. In some situations, especially on poorly drained soils, trees on sensitive rootstocks may be killed in severe winters. It should be stressed that many dwarfing rootstocks thrive best when the soil is well drained, either naturally or artificially. Where there is inadequate snow cover, coupled with very low temperatures, much damage is caused to the roots and shanks of sensitive rootstocks. After severe winter frosts, damage can frequently be observed as death of cambial tissues in the rootstock shank.

Rootstock breeders centred in Russia, Poland, the Ukraine, Belarus, Canada and the USA have made tolerance to low winter temperatures a principal goal in their programmes. However, care must be taken in choosing specific rootstocks from these programmes, as not all the selections exhibit cold tolerance. For instance, the Polish selections P.1 and P.16 show similar sensitivity to M.9

Table 5.4. Some of the traditional and recently released semi-dwarfing rootstocks for apples.

Rootstock name or number	Origin	Parents (if known)	Availability (2001)	Remarks	References
M.26	HRI-East Malling, UK	M.16 × M.9	Widely available	More vigorous than M.9, but less vigorous than MM.106; average yield efficiency; good fruit size and colour; anchorage better than for M.9 but needs staking on most exposed sites; most sub-clones burr-knot badly; winter-hardy; average drought tolerance; sensitive to woolly apple aphid and fire blight; poor calcium uptake on some sites; poor tolerance to heavy/wet soils; relatively easy to propagate	Preston, 1954, 1970; Rogers, 1958, Proctor <i>et al.</i> , 1974
B 62-396	Michurinsk College, Russia	Not known	Available for trials in several countries in eastern and central Europe	Vigour variable in trials in the Ukraine and Russia; usually between M.9 and M.26; very hardy; very limited trials/information available currently	Hulko and Hulko, 1999; Kapichnikova, 1999; Kuldoshin, 1999; Kurus and Ugolik, 1999; Verzilin <i>et al.</i> , 1999
'Bemali'	Balsgård, Sweden	'Mank's Codlin' × M.4	Limited availability	Vigour greater than M.9 and more similar to M.26; much less yield-efficient than M.9; produces small fruit size; better winter-hardiness than M.9; resistant to fire blight	Trajkovski and Andersson, 1980
G 11	Cornell University, New York, USA	M.26 × Robusta 5	Increasing availability	Similar vigour to M.26; similar or better yield efficiency than M.26; suckers; resistant to collar rot and to fire blight; very limited trials/information available currently in Europe	Johnson, 1999, Robinson <i>et al.</i> , 1999
J-TE-H	Techobuzice, Czech Republic	M.9 × 'Croncels'	Limited availability	Similar or slightly greater vigour than M.26, poor yield efficiency in some trials; very limited trials/information available currently	Dvorák, 1988
KSC 28	Kentville, Nova Scotia, Canada	'Beautiful Arcade' × 'Antonovka Kamenshka'	Available in Canada	Vigour greater than M.26; yield efficiency variable; winter-hardy	Privé and Embree, 1997
P.1	Sterniewice, Poland	M.4 × 'Antonovka'	Available in Poland	More invigorating than M.26; poor yield precocity and efficiency; severe burr-knotting; sensitive to viruses	Zagaja, 1980; Barritt <i>et al.</i> , 1995; Kruczynska and Czynczyk, 1998

P 14 (‘Skidal’)	Skerniewice, Poland	M.9 open-pollinated	Available in Europe	Vigour similar or greater than on M 26; good yield efficiency in Polish trials; poor precocity in Hungarian trials; very limited trials/information available currently	Czynczyk and Olszewska, 1990; Kurius and Ugolik, 1999
‘Supporter 4’ (‘Pillnitz 80’)	Dresden, Germany	M.9 × M 4	Available	Variable yield efficiency compared with M 26; hardy; easy to propagate	Fischer, 1997, 1999
V.7	Vineand, Canada	‘Kerr’ crab apple open-pollinated	Experimental root-stock still under evaluation	Vigour slightly greater than M 26; similar yield efficiency; winter-hardy; very limited trials/information available currently	Eifving <i>et al.</i> , 1993, Barritt <i>et al.</i> , 1995

Table 5.5. Some of the traditional and more recently developed semi-invigorating/invigorating rootstocks for apples.

Rootstock name or number	Origin	Parents (if known)	Availability (2001)	Remarks	References
M.7	East Malling, UK	Not known	Widely available	Similar to or slightly more invigorating than MM 106; induces average yield productivity; suckering often a problem; sensitive to winter-cold injury; field-tolerant to collar rot and fire blight; good adaptability to soil types	Hatton, 1917, Preston, 1970
MM 106	East Malling, UK	'Northern Spy' × M 1	Widely available	High yield efficiency; fruit size can be smaller than on M 9; good anchorage; few suckers; average tolerance of winter cold; some drought tolerance; susceptible to collar and crown rot, fire blight and tomato ringspot virus; resistant to woolly apple aphid	Preston, 1955, 1966; Parry, 1965
MM 111	East Malling, UK	'Northern Spy' × Merton 793	Widely available	Slightly more invigorating than MM.106; poorer precocity but good yield efficiency when trees mature; good anchorage; few suckers; some tolerance of winter cold; sometimes sensitive to collar and crown rots; resistant to woolly apple aphid	Preston, 1955, 1966; Parry, 1965
G.30	Geneva Research Station, New York, USA	Robusta 5 × M 9	Increasing availability	Similar vigour to M 7 in US trials, more yield-efficient and precocious than M 7; suckers; resistant to fire blight; resistant to crown rot; susceptible to woolly apple aphid; weak graft unions a problem; very limited trials/information available currently outside USA	Johnson, 1999, Robinson <i>et al.</i> , 1999
G.210	Geneva Research Station, New York, USA	Ottawa 3 × Robusta 5	Experimental rootstock still under evaluation	Similar vigour to M 7; yield efficiency similar to M.26 and better than M.7; suckers; resistant to collar/crown rot, woolly apple aphid and fire blight; very limited trials/information available currently outside USA	Johnson, 1999; Robinson <i>et al.</i> , 1999
KSC 7	Kentville, Canada	'Beautiful Arcade' × 'Antonovka'	Limited availability in Canada	Semi-vigorous to vigorous; average to poor yield efficiency; winter-hardy; very limited trials/information available currently	Privé and Embree, 1997

KSC 11	Kentville, Canada	'Beautiful Arcade' × 'Antonovka'	Limited availability in Canada	Semi-vigorous to vigorous; average to poor yield efficiency; very limited trials/information available currently	Privé and Embree, 1997
KSC 24	Kentville, Canada	'Beautiful Arcade' × 'Antonovka'	Limited availability in Canada	Semi-vigorous to vigorous; average to poor yield efficiency; very limited trials/information available currently	Privé and Embree, 1997
M.4	East Malling, UK	Originally 'Holstein Doucin'	Limited availability in genetic collections	Similar vigour to M 7; induces variable yield efficiency; poor anchorage; resistant to fire blight and to collar rot; poor uptake of potassium	Hatton, 1917; Preston, 1970
M.116 (AR.86-1-25)	HRI-East Malling, UK	MM 106 × M 27	Experimental rootstock still under evaluation	Induces vigour and cropping similar to MM 106, very resistant to collar/crown rot and to woolly apple aphid; only limited trials data currently available from UK and New Zealand	Webster <i>et al.</i> , 1986
MM 104	East Malling, UK	M.2 × 'Northern Spy'	Limited availability	Vigour slightly greater than MM 106; average precocity and productivity; tolerates dry soils; sensitive to collar and crown rots; resistant to woolly apple aphid and fire blight	Preston, 1955, Parry, 1965
V.2	Vineand, Canada	'Kerr' crab apple open-pollinated	Experimental rootstock still under evaluation	More invigorating than M 26 but less than P.1; good yield efficiency; winter-hardy; only limited information available from trials in countries other than the USA and Canada	Elfving <i>et al.</i> , 1993, Barritt <i>et al.</i> , 1995

Table 5.6. Some traditional and more recently released invigorating rootstocks for apples

Rootstock name or number	Origin	Parents (if known)	Availability (2001)	Remarks	References
Merton (MI) 793	John Innes Institute, UK	M.2 × 'Northern Spy'	Widely available in the southern hemisphere	Semi-vigorous to vigorous; induces poor yield precocity but average yield efficiency when trees mature; good anchorage; few suckers; resistant to woolly apple aphid and crown rot; very suitable for replant situations on poor soils	
'Alnarp 2'	Anarp Research Station, Sweden	Not known	Available	Very invigorating; poor yield efficiency; good anchorage and winter-cold tolerance	Pieniazek <i>et al.</i> , 1976
B 54-118	Michurinsk College, Russia	Not known	Available in Russia and some other parts of eastern Europe	Greater vigour than MM 106; variable yield efficiency; good anchorage; winter-hardy; good drought tolerance; resistant to fire blight	Hulko and Hulko, 1999, Kuldoshin, 1999
B 57-490	Michurinsk College, Russia	Not known	Available in Russia and some other parts of eastern Europe	Vigorous; poor precocity and productivity in Hungarian and Dutch trials; winter-hardy; resistant to fire blight; very limited trials/information available currently	Kurius and Ugolik, 1999
KSC 3	Kentville, Nova Scotia, Canada	'Beautiful Arcade' × 'Antonovka'	Limited availability in Canada	Very vigorous; yield efficiency good; good anchorage; winter-hardy	Privé and Embree, 1997
KSC 6	Kentville, Nova Scotia, Canada	'Beautiful Arcade' × 'Antonovka'	Limited availability in Canada	Very vigorous; average yield efficiency; good anchorage; winter-hardy	Privé and Embree, 1997
M.1	East Mailing, UK reselection	Originally named 'Broadleaved Paradise'	Available in genetic collections	Vigorous tree that exhibits poor yield efficiency; good anchorage, few suckers; susceptible to drought	Hatton, 1917
M.2	East Mailing, UK reselection	Originally named 'Dourin'	Available in genetic collections	Vigour similar to M.1; variable yield efficiency; only average fruit size; good anchorage; suckers; adapts to most soil types; some sensitivity to drought; tolerates wet soils; moderately resistant to fire blight; poor potassium uptake	Hatton, 1917
M.25	East Mailing, UK	'Northern Spy' × M 2	Limited availability	Vigour slightly greater than MM 111; high yield efficiency and precocity; good anchorage; few suckers; sensitive to woolly apple aphid	Preston, 1955, 1966; Parry, 1965
'Marubaka do'	Japan	<i>Malus prunifolia</i> 'Ringo'	Available in Japan	Very vigorous; only average induction of yield precocity and efficiency; resistant to woolly apple aphid and collar/crown rots	

MM 109	John Innes and East Mailing, UK	M.2 × 'Northern Spy'	Limited availability	Very vigorous; only average yield precocity and efficiency; poorly anchored; performs well on droughty soils; sensitive to collar and crown rot	Parry, 1965, Preston, 1966
'Novo e' PI286613	Geneva Research Station, New York, USA	<i>M. prunifolia</i> × <i>M. sieboldii</i>	Limited availability in the USA	Very vigorous; unpalatable to voles; resistant to apple scab, fire blight and tomato ringspot virus; variable resistance to crown rot; easily propagated from softwood or hardwood cuttings but difficult by layering; minimal suckering	Ferree and Carlson, 1987; Wertheim, 1998
V.4	Vineand, Canada	'Kerr' crab apple open-pollinated	Experimental rootstock still under evaluation	Vigorous; average yield efficiency; winter-hardy; very limited trials/information available currently	Elfving <i>et al.</i> , 1993, Barritt <i>et al.</i> , 1995

For a full review of breeding for cold tolerance in apple rootstocks the reader should consult Hulko and Hulko (1999). Where known, the cold tolerances of many of the traditional and new clonal rootstocks are mentioned in the Remarks sections of Tables 5.1 and 5.3–5.6.

5.10.2 Tolerance to soil-borne or aerial pathogens

The roots and below-ground parts of apple rootstocks may be attacked by many fungi and bacteria and the most damaging of these may result in tree death. The most common species of fungi causing damage to the rootstocks are the collar or crown rots (*Phytophthora* sp.) and several studies have investigated rootstock sensitivity to these pathogens (Lemoine and Gaudin, 1991). Among the super dwarfing rootstocks, P.22, G.65, JM.1, JM.5 and JM.8 are reported to show good resistance, while M.9, Ottawa 3, P.2, P.16, G.16, B.9, Mark and J.9 all show resistance in the dwarfing category. Other more invigorating rootstocks showing resistance are G.11, G.30, G.210, M.116, M.7 and 'Marubakaido' (see Tables 5.1 and 5.3–5.6).

Less common but very damaging are the honey fungus (*Armillaria mellea sensu stricto* Vahl. ex Fr.) and other species classed in the USA as the southern root rots. Unfortunately, few, if any, apple rootstocks show resistance to these root rots. The bacterial pathogen crown gall also attacks apple rootstocks and may stunt growth severely in some soil conditions. Although no rootstocks are fully resistant to crown gall, clones do differ slightly in their sensitivity.

Aerial pathogens such as apple scab (*Venturia inaequalis* (Cke.) Wint.) and apple powdery mildew (*Podosphaera leucotricha* (Ell. & Ev.) Salmon) attack rootstocks in the same way that they attack apple scions and protective spray programmes must be applied in the nursery to prevent damage. Apple canker (*Nectria galligena* Bres.) may also prove a problem in some countries and it has been suggested that this pathogen may, in some circumstances, be carried in rootstocks and young trees produced in the nursery. Often no

symptoms show until several years later, following planting of young trees in the orchard.

Important though these pathogens are, they are minor compared with the damage caused by fire blight in some apple-producing regions of the world (Ferree *et al.*, 1983; Perry, 1992). Rootstocks that are not only resistant to fire blight but that also confer some of this resistance to scions budded or grafted would be of great value in the eastern states of the USA. Amongst the currently available rootstocks exhibiting some resistance to fire blight are G.65, G.16, G.11, G.30, G.210, Bemali, M.7, M.4, M.2, MM.104, B.118 and B.490 (see Tables 5.1 and 5.3–5.6).

5.10.3 Tolerance to soil-borne or aerial pests

The most damaging pest affecting apple rootstocks is the woolly apple aphid (*E. lanigerum*), which can cause significant damage to roots of apple trees if they are planted on susceptible rootstocks in apple-producing areas where the pest is present and where soil conditions favour it. Hot and dry soils, such as those commonly used for apple production in the southern hemisphere, are particularly prone to damage from woolly apple aphids, although less severe damage is also noted in parts of southern Europe and in Israel. Most dwarfing rootstocks are sensitive to the pest, although recent reports suggest that several rootstocks bred in Japan (JM series) may combine dwarfing with resistance. Merton 793 and the MM series of rootstocks, all bred using the resistant scion cultivar 'Northern Spy' as one parent, exhibit tolerance to the pest, as does the Japanese selection 'Marubakaido'. Among the more recently selected apple rootstocks, M.116 and G.210 both show tolerance (see Tables 5.1 and 5.3–5.6).

Soil-borne nematodes can also cause significant damage to apple rootstocks and this is mainly a problem when planting trees on shallow, dry and acidic soils. Fortunately, the main apple-producing regions of the world only occasionally experience severe problems with nematode damage. However, the nematode species *Pratylenchus penetrans* (Cobb) Sher & Allen has been reported to

cause damage and poor tree establishment on sandy soils in The Netherlands.

5.10.4 Tolerance to drought or soil asphyxiation

Supplies of water for irrigation of apple orchards are often limited, expensive or both. Use of trickle irrigation delivery systems can significantly improve the efficiency of water use and is recommended for many areas rather than the less efficient overhead or flood irrigation methods. Nevertheless, rootstocks that aid efficient water use by the tree will become more important in the future.

Unfortunately, most dwarfing rootstocks require some additional water supplied via irrigation if they are to grow and crop well in areas experiencing very hot, dry summers. Growers choosing organic systems of apple production cannot use chemical herbicides and are often obliged to let weeds grow for longer periods than are ideal beneath their trees. Weeds and grass compete strongly for water, and tree growth on dwarfing rootstocks can be severely impaired by excessive weed growth.

On stony, well-drained soils, water retention within the profile is poor and, unless the tree's root system is able to penetrate deeper into the profile to tap water reserves, apple trees will suffer drought stress.

In these and several other situations, rootstocks exhibiting tolerance to transient drought conditions can be a great aid to successful apple production. As a general rule, the more invigorating the rootstock, the less likely it is to suffer from drought. A few of the rootstocks exhibiting some drought tolerance are described in Tables 5.1 and 5.3–5.6

5.11 Use of Interstocks and Interstems

Interstock or interstem trees are comprised of three genetically different components (Fig. 5.6).

Traditionally, interstocks (interstems) were used in raising fruit trees only when

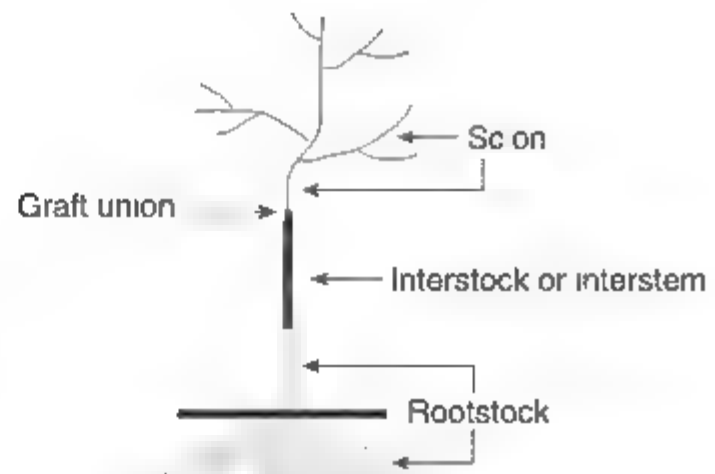


Fig. 5.6. Dwarfing interstock/interstem in relation to apple scion and rootstock.

graft compatibility between the rootstock and scion was a problem. This is a common practice when raising certain cultivars of pear on quince rootstocks. Interstock use in apple is less widespread and is generally only applicable when either the desired dwarfing rootstock is difficult to propagate on its own roots (e.g. Ottawa 3) or the soils are unsuited to planting dwarfing rootstocks (e.g. infested with woolly apple aphid or subject to drought or waterlogging). Trunk builders or 'staddles' of winter-hardy cultivars, such as 'Hibernal', have been used for a very long time in central Europe to prevent freeze damage to the tree trunk, and cold-tolerance benefits have also been recorded when using interstems of more usual length (Wertheim, 1985).

It is fortunate that, for reasons not understood, a significant part of the dwarfing influence of an apple rootstock is attributable to factors associated with its shank (stem piece) rather than its root system. This means that, by inserting a short length of the dwarfing rootstock as an interstock between a more invigorating rootstock and the scion, the grower can achieve semi-dwarfed trees. Up to approximately 35 cm in length, the longer the interstock stem piece, the more dwarfing the effect (Parry and Rogers, 1972). Trials in Poland have shown increased productivity when using P2 as an interstock (Kruczynska and Czynczyk, 1998).

Trees raised with interstocks are slightly more expensive to produce but often their

benefits warrant this extra expenditure by the grower. Further information on raising trees with interstocks (interstems) can be found in Chapter 6.

Occasionally, stem pieces of other scion cultivars (such as 'Golden Delicious' or 'Summerred') are inserted between the rootstock and the chosen scion. This can improve

the precocity of cropping and winter-hardiness of the tree. Interstocks can also help regulate the vigour of shoot growth on the scions (Wertheim and Callesen, 2001). Also, in The Netherlands an interstem of 'Dubbele Zoete Aagt' is used with the scion cultivar 'Cox's Orange Pippin' to prevent trunk rot caused by *P. cactorum*.

Further General Reading on Apple Rootstocks

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6 Propagation and Nursery Tree Quality

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6.1 Introduction

In nature, apple trees multiply by seeds, but when apple trees are grown commercially or by the home gardener the common propagation method is to bud or graft scion cultivars on to selected rootstocks. The reason for propagation by means of rootstocks is that apple cultivars are not true to type when propagated by seed and, at least in former days, difficult, if not impossible, to propagate by vegetative means. Thus, when a seedling with good fruiting characteristics was found, it could not be multiplied by sowing its seeds or by use of layering or cutting techniques. Today, vegetative propagation techniques have improved so much that scion cultivars can be multiplied by cuttings or by micro-propagation in the laboratory. Nevertheless, the use of rootstocks has remained dominant, because most of the currently grown scion cultivars, once self-rooted, do not perform well in the orchard. Scion trees propagated 'on their own roots' are more vigorous, come later into bearing and crop less efficiently than those on good rootstocks.

Apple seedlings must have been the first rootstocks used extensively by early horticulturists, largely because seeds were readily available. Only after it was observed that some apple cultivars could be easily propagated by layering did vegetative or clonal propagation come to be considered as a useful means of propagating valuable scion cultivars. It must soon have become clear that 'clonal' (vegetatively propagated) rootstocks had great advantages over seedling rootstocks. First, there was the possibility of adapting the performance of the scion cultivar in a desired direction. This was important and remains especially so today for tree vigour, precocity and cropping efficiency. Secondly, orchards on clonal rootstocks were uniform in growth and cropping, while those on seedling rootstocks were more variable because each scion tree is propagated on a distinct genotype. Today, there is a worldwide trend towards 'intensive' apple growing with scion trees grown on rootstocks that are more or less dwarfing. Such intensive planting systems are easy to manage and provide growers with early returns on invested capital.

Hereafter, the propagation methods for apples are reviewed, with emphasis given to propagation on (moderately) dwarfing rootstocks. For a successful modern orchard, the planted tree must be of high quality, and attention will also be paid to the raising of trees capable of early cropping.

Recent reviews on rootstock propagation include Howard (1987) and Webster (1995).

6.2 Seed Propagation

Although seedlings are still widely used as rootstocks for raising apple trees, this use is on the decline in most countries. Trees raised on the seedling rootstocks that are currently available are too vigorous and variable for modern fruit growing. However, seedlings do have several advantages compared with clonal rootstocks. They are easily and cheaply produced, virus-free (as viruses are not transmitted through apple seed) and, if raised under certain conditions, free of soil-borne root diseases, such as crown gall (*Agrobacterium tumefaciens* (E F. Smith & Townsend) Conn.). Orchard variability in the growth and cropping of apple scions raised on seedling rootstocks can be reduced by collecting seeds from special seed orchards. Here, only a tried and tested combination of two clonal cultivars or one self-fertile cultivar is grown for seed production. 'Delicious' (USA), 'Antonovka' (eastern Europe) and 'Bittenfelder' (western Europe) are all recognized seed sources, but other cultivars are used elsewhere. Seed plantations should be located far from other orchards to prevent unwanted cross-pollination. A further measure to reduce variability in performance of seedling rootstocks is seed grading and the use of only the largest seeds, as these produce the best plants.

Fruit from seed orchards is harvested by hand or by mechanical shakers and the seeds are separated from the fruit. Apple seeds cannot germinate directly after harvest and extraction from the fruits, because they are dormant (Dennis, 1994). To remove seed dormancy, seeds must be stored for a certain period at low, but above-freezing, tempera-

tures with adequate moisture and air – a process called stratification. The most effective stratification temperatures for apple are 2–6°C, with an optimum at 4°C. Ninety days at 4°C can result in 100% seed germination (Seeley and Damavandy, 1985). These figures are indicative only and vary with seed source, year and the fruit-storage regime (Perino and Côme, 1979). After stratification, apple seeds germinate best at temperatures from 10 to 20°C; at 30°C a secondary dormancy arises (Perino and Côme, 1977).

Seed stratification is carried out in special cases in cold-storage rooms at 2–4°C. The seeds are placed either in sand or peat or without any substrate, but it is essential that the seeds do not dry out. After stratification, seeds are sown at about 2 cm depth. At an early stage of growth the primary or tap roots are mechanically removed by undercutting the seedling rows. Planting distance will depend on local conditions, the objectives of the nurseryman and the machinery available; a within-row distance of 20 cm is commonly used (Bartels, 1982).

In the past, it was thought that apomictic seedlings of various *Malus* species closely related to the cultivated apple might have a future as rootstocks of very uniform performance. All apomictic seedlings are identical to the mother-parent cultivar, as they arise from maternally derived cells within the ovary and not from the fertilized egg cell. Apart from giving uniform performance as rootstocks, apomicts are also virus-free. However, the apple types used are only 'facultative apomicts'. This means they produce a mixture of apomictic and zygotic seeds and the two must be separated in the nursery; this proves to be a cumbersome and often difficult activity. Most of the types of apomictic seedlings evaluated as rootstocks also proved to be rather vigorous. Moreover, when a scion cultivar contained latent viruses and the apomictic rootstock type was hypersensitive, incompatibility could occur, although this defect can be solved by using virus-free scion material (Schmidt, 1988). For these shortcomings and because of the strong market demand for dwarfing clonal rootstocks, apomictic seedlings are not used in commercial apple growing.

The continuous use of 'conventional' (i.e. not apomictic) seedlings is partly due to their easy availability and is also attributable to the rather conservative attitudes of certain rootstock suppliers and apple growers.

Seedling-raised rootstocks of several *Malus* species do prove to be of value in improving the tolerance of apple trees to drought conditions. *Malus sieversii* Ldb. or *Malus prunifolia* Willd. seedlings are commonly used in parts of China with this objective and similar seedling rootstocks are used in Japan. Where control of tree vigour is required on seedling rootstocks, a dwarfing interstock, such as M.26, is used. Seedling rootstocks continue to be used, albeit much less than in the past. In the USA, they are mainly used with compact scion cultivars of 'Delicious', such as 'Red Chief' or 'Oregon Spur', where vigour control is achieved via the scion.

6.3 Vegetative or Clonal Propagation

New plants identical to a parent plant can be produced by division (stooling or layering) or by cutting techniques. In the former case, young plants remain attached to the mother plant until they have formed roots and are able to develop independently. Stooling and layering are long-established methods of division (Knight *et al.*, 1928; Anon., 1963) and are still the most common propagation methods for apple rootstocks. With cutting techniques, young plant parts are separated from the mother plant in summer or winter and are then induced to form roots. In the former case, leafy shoot tips collected in spring or early summer are rooted in glasshouses under high humidity; these are often referred to as softwood cuttings. In the case of winter cuttings, leafless 1-year-old shoot parts are collected and their rooting induced in a suitable medium with bottom heat. Occasionally, semi-hardwood cuttings, taken in late summer once shoot growth has terminated, have been used for propagation of apple rootstocks, although this is not a common practice. Micropropagation is another, relatively new, method used for propagating both rootstocks and scions. Here, tiny plant parts are

separated from the parent plant, for example growing shoot tips, and multiplied and rooted on special media (*in vitro*) under sterile conditions in the laboratory. All the above methods have their strong and weak points and all can be used for the propagation of both scion and rootstock cultivars. Given the shortcomings of self-rooted scion cultivars, the methods are mainly used in rootstock propagation. Whatever the method of propagation, it is recommended that, where available, only virus-indexed material that is healthy and true to type should be used. To ensure healthy and true-to-type stock, the safest course of action is to use only material obtained from organizations that have been officially commissioned to maintain and distribute healthy propagation materials.

6.3.1 Stooling

With stooling (stool or mound layering), 1-year-old rooted plants are planted vertically in spring and left unpruned for 1 year. In the following spring, the stems are cut back to 2–3 cm above the ground and the arising shoots are partly covered with earth several times during the growing season. This is mainly done mechanically but, if needed, additional handwork can be involved, especially at the first covering ('earthing up'). Covering the shoot bases must be done carefully and in such a way as to leave a sufficient amount of the leaves exposed to the light but at the same time to blanch the basal part of the stem to facilitate rooting. Severe pruning and blanching are both essential for successful rooting in the stool bed (Howard *et al.*, 1985).

To allow earthing up, distances between rows of stools should be adequate – at least 1 m. Within the rows, stools are spaced 30 cm apart. When the young shoots are about 10–15 cm long, friable soil is carefully drawn up to the rows and in between the plants, so as to cover up shoots to half their total lengths. A second earthing up is done when the shoots are approximately 20–25 cm long and a final one when shoots have grown to about 45 cm. After this final cultivation, 15–20 cm of the shoot bases should be covered with soil and it is there that the rooting

takes place. The number of times that shoots are earthed up varies and depends on local practice. As well as soil, peat mixtures or sawdust are also used for earthing up in the stool beds. However, care must be taken to ensure that the sawdust used contains no substances inhibitory to rooting.

After natural leaf drop, the ridge of soil or other substrate is ploughed and/or forked away and the rooted shoots are cut loose from the parent plants. Depending on the climate, the removed soil or substrate is raked back over the stools after harvest to protect them from winter injury. The above cycle of production is repeated annually and, provided that no diseases or pests interfere, the stock plants should continue to produce rooted shoots of adequate quality for at least 15 years.

Rootstock clones differ in the number of rooted shoots ('liners') that are produced annually per stool plant or per metre stool bed. Average annual yields of first- and second-grade shoots obtained at East Malling Research Station varied between 2.6 per stool for M.9 to 13.4 for MM.104 (Howard, 1977). Production figures from trials conducted earlier on 4-year-old stools planted at 60 cm apart in the row at the same research station ranged from a total of nine plants (of which four were first-grade liners) per stool for M.9 to a total of 24 (with 18 first-grade liners) for M.13 (Knight *et al.*, 1928).

The productivity of stools is negatively affected by the presence of viruses (Campbell, 1961) or by using liners that are too small to establish the stool beds, even when a 2-year establishment period is used (Howard, 1977). By biennial harvesting, the number of large liners produced, which are needed where high budding is to be practised, can be increased. This method decreases the number of non-rooted shoots, welcome in the case of shy-rooting rootstocks, such as M.27. However, negative features of biennial harvesting are the increase in plants with lateral shoots, which are a nuisance when budding, and the number of misshapen and mildew-infected (*Podosphaera leucotricha* (Ell. & Evi) E.S. Salmon) plants (Vasek and Howard, 1984). A way to improve the performance of stool beds is to

kill the weak growths that develop early in the season on stumps of weak shoots left after harvesting and pruning in the previous year. At about 5 cm length, these shoots can be easily eliminated using one spray of 4% 'Tipp-off' (naphthaleneacetic acid (NAA) plus decanol and emulsifiers). Provided the growth of the stool plants is vigorous, more large-rooted shoots suitable for high budding can then be harvested (Howard, 1984). The same objective can also be achieved by removing the weak shoots by hand.

The stool harvest consists of 'liners', 'non-liners' and non-rooted plants. Liners are rooted plants of adequate size suitable for lining out in the fruit-tree nursery for budding. Non-liners are rooted but too thin for budding in the following spring/summer. Both, non-liners and the non-rooted plants that are not too small are planted ('bedded in') at close between-plant spacings (7.5–10 cm) for a further year for additional thickening and/or rooting. They may be used for late-summer budding in these 'waiting' beds or lined out in the subsequent season. Very small rootless plants are usually discarded.

Apple-scion cultivars can also be successfully multiplied by stooling (Schimmelpfeng, 1963), although this is rarely practised commercially.

6.3.2 Layering

One-year-old plants are planted in rows, which are preferably north-south-orientated, at an oblique angle of 30–40° to the horizontal and left unpruned for one growing season. The following spring, the stems are bent and secured flat to the ground and the shoots that arise on these horizontal layers are regularly and carefully earthed up, just as with stooling. In trench layering, the mother plants are planted in a shallow trench so that when bent horizontally the layers are just below ground level. In this method, which is often used with stone fruits, the layered shoots can be covered with a few centimetres of earth just before bud break. For apple, however, this is not necessary and the mother plants are usually planted on flat land. To prevent damage to

the horizontal layers by the circular saws used at harvest, the land surface must be completely flat with all plants maintained in a horizontal plane.

In The Netherlands, the procedure used for layering M.9 is as follows. The plants are planted obliquely at 30 cm spacings in the rows, which are 75–100 cm apart (Plate 6.1). November is the optimum planting time, but this depends on weather and soil conditions. For establishment, plants with a stem diameter of 8–10 mm measured at ground level are used. After one growing season, the plants are forced horizontally by braiding (tying) them together, including any side-shoots that may have arisen. Given the close planting distance in the rows, there is an overlap of shoots from adjacent layers that facilitates braiding and contributes to high production. The first earthing up is carried out when the shoots are 20–25 cm long and either soil or peat mixtures are used. The peat is brought into the rows using machines, but handwork may be needed for distributing soil or peat evenly between the shoots. At intervals of approximately 1 month, two further earthings up are undertaken. On these occasions, soil is usually used and the shoots are partially covered to leave half of their lengths exposed. The rooted shoots are cut off with a circular saw before winter (Plate 6.2) but after leaf drop, and are stored indoors at 1°C at high humidity. The saw cuts the shoots at about 1 cm above the horizontal layers and the below-ground blanched section should be at least 15 cm long. When properly fertilized and managed, especially in regard to crop-protection sprays, layer beds continue to produce well for more than 15 years.

In practice, 20–25 well-rooted plants of more than 5–6 mm basal stem diameter per metre of row length can be obtained, plus 15–20 plants that are too thin for immediate use as liners (less than 5–6 mm diameter). These thin rootstocks are planted for another year at close spacings (10 cm in rows 50 cm apart) in a waiting bed. M.9 plants destined for budding are of various basal stem diameter classes (5–7 mm and 7–9 mm or 6–8 mm and 8–10 mm), depending on the particular practices of the nursery. Plants over 9 or 10 mm in diameter are used for bench grafting.

Yields of layer beds depend on the growing conditions (soil and climate), age, health (especially virus) status, rootstock clone (or even sub-clone) and efficiency of management. Layer beds start to produce in the second season following planting, and production increases in the following few years before stabilizing at a constant output (Plates 6.3 and 6.4). The difference in the production level of a layer bed at an early and in a mature stage is approximately 30% (Table 6.1). The 8-year average gives an indication of the performance of M.9 layers of different origins. Juvenile sub-clones of this rootstock, such as Fl.56 and RN 29, are more productive than the non-juvenile T.337. A virus-infected sub-clone (B.984) gives poorer production. Approximately 40–50% of the yield consists of plants suitable for budding and about 5% for bench grafting (Table 6.1). The rest must be grown on for another year.

The occurrence of M.9 sub-clones in juvenile, adult and transitional stages is due to their maintenance in certain ontogenetic stages (van Oosten, 1986). Production of M.26 has also been shown to vary with the sub-clone; juvenile types again producing more than adult ones (Table 6.2). The propa-

gation method also had an effect; *in vitro* plants were more productive than those obtained by conventional layering (see section on micropropagation). It should be mentioned that both the *in vitro* and the layer plants of each of the three sub-clones originated from a single plant. Material of that plant was either put through *in vitro* culture and thereafter the shoots produced used for layering or the plants were solely propagated via a layer bed. These differences in origin did not affect subsequent orchard performance (Wertheim and Kunneman, 1993).

With P.22, similarly, *in vitro* culture produced juvenile plants clearly different from those obtained solely through layering. Compared with the adult type, the juvenile sub-clone was characterized by smaller leaves, more laterals, a spreading habit, a higher production per metre layer bed and a higher rooting percentage. However, the pendulous habit of the juvenile sub-clone was a nuisance for nursery management (Wertheim, 1991). The differences in sub-clones had no consequences for the subsequent orchard behaviour of trees raised upon them. A good sub-clone for the rootstock propagator, however, need not neces-

Table 6.1. Production of a layer bed (in plants per metre row length and greater than 4 mm diameter) of virus-free M.9 sub-clones planted in spring 1983 at 1.25 × 0.25 m between- and within-row spacing (Data from Versteegen and Verstraelen, 1992)

Parameter	Sub-clones			
	T.337	Fl.56 ^a	RN.29 ^a	B.984 ^b
Average 1984/85	20.5	22.3	22.7	16.9
Average 1990/91	31.6	34.6	42.8	25.5
Average 1984–1991	26.6	29.0	32.5	21.3
Averaged for 1984–1991				
Rooted plants (%)	89	94	94	86
Spurred plants (%)	6	7	13	3
Plants 4–6 mm ^c (%)	46	50	44	47
Plants 6–8 mm ^d (%)	33	33	33	33
Plants 8–10 mm ^d (%)	15	11	16	14
Plants 10–12 mm ^e (%)	5	3	5	5
Plants > 12 mm ^e (%)	2	2	2	1

^aJuvenile sub-clone

^bNon-virus-free

^cFor bedding

^dFor budding

^eFor bench grafting

NB. Spurred plants have short laterals.

Table 6.2. Production of layer beds (in plants per metre row length) of virus-free M 26 sub-clones planted in spring 1989. Plant material of each sub-clone was propagated by layering, but the layer beds were established either from a maternal layer bed or from *in vitro* culture, using one single plant as the source of all plants. (Data from Denissen *et al.*, 1993.)

Propagation method	Sub-clone	Character	Plants m ⁻¹		Stem diameter (mm)	
			1991	1992	1991	1992
Layering only	IVT	Non-spurred	16.0	25.0	9.2	7.3
	NAKB	Non-spurred	19.4	27.0	8.5	7.1
	NAKB	Spurred ^a	26.1	37.4	8.8	7.0
	Average		20.5	29.8	8.8	7.1
Layering after <i>in vitro</i>	IVT	Non-spurred	18.5	26.2	9.4	7.7
	NAKB	Non-spurred	24.5	35.2	8.7	7.0
	NAKB	Spurred ^a	33.4	49.0	8.2	6.7
	Average		25.5	36.8	8.7	7.0

^aJuvenile type

sarily be the best one for the following users of that material (including the raisers of scion trees and fruit growers). Juvenile clones may have more spines or laterals, which are a nuisance with budding, and may be more prone to sucker and burr-knot formation in the orchard. Suckers can be points of entry for pests and diseases; burr knots have reduced cold-hardiness and cause tree-to-tree variability.

Compared with M.9, layer beds of other popular rootstocks, such as M.26, MM.106 and MM.111, can be more productive, those of M.4, M.7, M.27, J.9, B.490, B.491, P.16 and P.18 as productive and those of P.1, P.2, P.22, B.9, O.3 and M.25 less productive (Quamme and Brownlee, 1990). It should be realized, however, that yields may be affected by the sub-clone chosen.

In both stooling and layering, the emergence of roots appears to be largely confined to nodal positions near lateral buds, probably because the mechanical restriction there is the least. Blanching (i.e. partial etiolation) causes an increase in starch in the parenchymatous bud and leaf gaps and in the outer ring of pith cells of the stem, together with a decrease in the degree of sclerification of the cortex. A high starch content favours root formation, perhaps because it provides more energy, and rooting appears to be negatively correlated with the degree of sclerification. Easy-to-root rootstocks, such as MM.106, have a lower percentage of sclerification than

more difficult-to-root rootstocks, such as M.9 and M.26 (Doud and Carlson, 1977).

Shoots derived from stools or from layers are not completely uniform. This may be because of their different position of origin relative to the roots. Those arising close to the roots may be slightly more vigorous and bear more laterals or spines than those originating more distally. Root hormones may be involved here, although there is little evidence to support this hypothesis. In a Dutch trial, orchard performance of M.27 rootstocks separately harvested from basal or apical parts of layers was similar. The former were slightly more vigorous and had a few laterals, while the latter had none.

6.3.3 Cuttings

Propagation of apple rootstocks or scions by hardwood or softwood cuttings is not widespread. Stooling and layering techniques are currently perceived to be more reliable and less expensive. Details on cutting methods are given by Hartmann *et al.* (1990) and on stock-plant manipulation by Howard (1994).

6.3.3.1 Hardwood cuttings

Propagation by hardwood cuttings is sometimes seen as a preferred alternative to layering, because shoots can be harvested from stock plants each year in numbers

determined by demand. However, hardwood cuttings of apple rootstocks usually require growing in the nursery for a year before they can be budded (Plate 6.5). This means that demand for rooted liners suitable for budding must be known 2 years in advance if the technique is to have significant advantages. Research, mainly carried out in England, has shown that it is possible to root hardwood cuttings of apples, provided that the bases are treated with auxin and given a brief treatment at high temperature. Wounding the base of the cutting also has favourable effects on rooting (Howard, 1987).

Current-year shoots are cut after leaf fall in autumn or early winter from hard-pruned stock plants. These should be virus-free, as the presence of viruses reduces shoot production, subsequent root formation and establishment (Howard, 1972). The stock plants are planted in hedgerows at distances suitable for management by tractors or other machinery. Distance between stock plants in the rows should be at least 30 cm. After removal of the cuttings from hedge plants, the remaining shoots are shortened to three or four buds to ensure vigorous growth in the subsequent year. Shoots from vigorous plants have a higher rooting potential than those from lightly or non-pruned plants and those from low hedge plants root better than those from high plants. Thus, hedges are kept at about 1 m in height (Plate 6.6). The rooting potential is highest at the shoot base and this part must be included in the cutting. When the cutting includes the basal ring of buds near the old wood it is called 'basal nodal', when the cut is made a node higher 'non-basal nodal' and if cut between this and the following node 'non-basal internodal' (Howard *et al.*, 1984). Cutting length depends on planned planting depth and budding height and varies between 40 and 60 cm. Cuttings are shortened distally to the required length. Growing cutting hedges in a polyethylene tunnel increases vigour, rooting percentages and roots per cutting (Campen *et al.*, 1990).

Applying auxin to the cut surface greatly enhances rooting. The most effective auxin is indole-3-butyric acid (IBA). For apple, the

preferred method of application is to dip the cutting bases for 5 s into a 1 cm deep solution of 2500 p.p.m. IBA in a 50% aqueous solution of acetone, but other methods and carriers can be used. Too high concentrations of auxin may contribute to basal rotting and should be avoided. After the auxin treatment, cutting bases dry naturally before being inserted into a rooting medium. Auxin treatment also stimulates successful establishment of the cutting. Optimal establishment is usually achieved by planting in February (northern hemisphere). Visible roots are not necessary on transfer to the field, but the presence of healthy callus is (Howard, 1968, 1978, 1985, 1987; Howard *et al.*, 1984; Campen *et al.*, 1990).

In the rooting medium, the cutting bases are subjected to a period of relatively high temperature. The heat treatment operates additively to and independently of the auxin treatment. A suitable medium is needed to minimize rotting, and mixtures of peat with adequate amounts of coarse-particle materials, such as sand, grit or perlite, are satisfactory. The medium should be able to hold the cuttings in place, provide moisture, permit air penetration and gas exchange and create a dark environment suitable for rooting. Good drainage of the rooting medium is a necessity because, although hardwood cuttings take up water from the medium, they cannot transpire it rapidly as they have no leaves. As a consequence the cutting bases can rot if inserted into medium that is too wet and/or poorly drained. At Horticulture Research International (HRI), East Malling, an 8 cm layer of granulated pine bark over 20 cm fine sand is successfully being used with a heating mat situated on top of the sand. Bundles of cuttings are put into the bark so that their bases are about 3 cm above the heating elements. The optimum temperature of the rooting medium at the cutting base depends on the cultivar, but in general 20°C is recommended for apple (Howard, 1987). However, the apple scion cultivar 'Cox's Orange Pippin' reacts better to 30°C (Webster *et al.*, 1990). The duration of the heating period depends on the time of the year and the cultivar. In February, 2–3 weeks suffice, while in midwinter 4 weeks are bet-

ter. Easy-to-root cultivars need less time than difficult-to-root ones. For the former, a good indication of successful stimulation is the presence of healthy callus and only a small percentage should show a few roots. Difficult-to-root cultivars require the presence of a few roots on all cuttings for good subsequent establishment. The rooms where cuttings are treated (in what are often called 'Garner bins') have minimum light and 90% humidity and are cool (max. 10°C) to prevent bud break. Under humid conditions, cuttings root best in late autumn and again in late winter and spring, but less well in midwinter. Under 50–60% humidity this trend is reversed. After heat treatment, cuttings can either be planted in the nursery for budding in the summer or in waiting beds of compost to establish further (Howard, 1987; Webster *et al.*, 1990).

Rooting is stimulated by wounding, but only in the presence of auxin. Splitting the shoot base for a length of 2 cm is especially effective (Howard *et al.*, 1984; Howard, 1987, 1994). Possibly, this splitting acts by breaking the sheath of sclerenchyma tissue that blocks root emergence. In apple shoots, such a sheath of fibres and sclereids occurs in the primary phloem. Difficult-to-root apple cultivars have a more complete sheath than easily rooting ones. The development of sclerenchyma tissue takes place during shoot growth. It may vary between apple cultivars and is subject to variation in the environment. Formation is retarded by shading and etiolation. Partial etiolation occurs in earthing up of stools and layers and in banding shoots with opaque tape (blanching), and these measures enhance rooting. If the development of the sheath is rapid and is near the stem tip, rooting of summer cuttings is difficult. Although it takes longer, rooting of young shoot tips under mist is possible (Beakbane, 1961, 1969; Pontikis *et al.*, 1979) (see paragraph on summer cuttings). However, other factors than the sclerenchyma sheath are involved in differences in rooting potential among cultivars. For example, the presence of preformed root primordia in the cortex varies between cultivars. In M.7, M.27, MM.106, Mo84 and the new dwarfing rootstocks Q9, Q60 and Q64

such primordia are present, but not in M.26 and M.9. In MM.106 and Mo84, primordia are present in the cortex around the bud and new roots emerge from that area. The presence of preformed roots is an advantage in propagation by cuttings. In M.26 and M.9, roots have to be formed from newly formed callus at the basal cut surface. In Mo84, roots can emerge both from callus and from buds and lenticels, which is favourable for hardwood-cutting propagation in the field. When the basal cut surface rots, roots can still emerge from lenticels and buds above the rotted area. In the new dwarfing rootstock Q9, root primordia occur in both nodal and internodal areas and this will further contribute to easy propagation (Fukuda *et al.*, 1988). Differences in hormone metabolism may further contribute to the variable rooting ability of apple cultivars (Hartmann *et al.*, 1990).

Hardwood cuttings are being used to some extent for easy-to-root apple rootstocks, such as M.26, M.27, MM.106 and MM.111, and for non-rooted shoots from stool or layer beds. In future, more rootstocks will certainly be added to this list.

6.3.3.2 Softwood cuttings

Softwood cuttings are quite small in size, to minimize water loss, and are therefore less suited to rootstock production. This is because it takes too long before rootstocks suitable for sale or for budding are obtained. Softwood cuttings can, however, be useful for the rapid multiplication and build-up of a new rootstock cultivar (Howard, 1987). Softwood or summer cuttings are also of practical value in certain specific situations. In Norway, import of rootstocks is prohibited for phytosanitary reasons and the growing season is too short for successful layering (Billing Hansen, 1990).

Softwood cuttings are young extension shoots that are cut in spring or early summer from hard-pruned stock plants. Shoots from stools root better than those from hard-pruned 1 m high hedges. It appears that the rooting potential of the cuttings increases with increasing severity of pruning and decreasing distance between the position of

the cutting on the stock plant and its root system (Nelson, 1976; Howard *et al.*, 1985). Stock plants derived from *in vitro* material produce cuttings that root more easily than conventionally propagated stock plants (Quamme and Hogue, 1994). Also, stock plants that have been kept in the shade for a while from bud break onwards give better results than plants growing in full daylight. The first cuttings obtained from stock plants in the growing season give higher rooting percentages and numbers of roots per rooted cutting than later collections (Delargy and Wright, 1978; Howard *et al.*, 1985; Billing Hansen, 1989, 1990; Grzyb *et al.*, 1989). Cuttings are preferably made early in the morning when shoots and leaves are turgid. To prevent wilting, transfer of the cuttings to the rooting environment (glasshouse or polyethylene tunnel) must proceed quickly and, if necessary, the cuttings must be dipped into water and transported in plastic bags containing some water.

Various shoot parts and various lengths of cutting have been successfully used with apple, as illustrated by the following examples. Shoots can be collected in late June (northern hemisphere) from outdoor stock plants using the proximal 20 cm with three to four leaves. These are trimmed to a node and defoliated at the lower end for about 7 cm (Howard *et al.*, 1985). Short shoots up to 8 cm long developing from forced stock plants in a glasshouse cut at their base can also serve as good starting material (Billing Hansen, 1990), as can regrowths just exceeding 13 cm from rootstocks pruned at ground level (Nelson, 1976). In all these cases, the lower leaves are removed. Four-node cuttings perform better than smaller ones, possibly because their reserves are greater (Schmadlak, 1969). In the case of long cuttings, the proximal halves root better than distal ones (Quamme and Hogue, 1994).

Exogenous auxin is necessary for the rooting of softwood cuttings and more so for difficult-to-root cultivars than for easy-to-root ones. The cutting bases are dipped for 5 s in a 50% aqueous acetone solution containing 2500 p.p.m. IBA to a depth of 8 mm and allowed to dry (Howard *et al.*, 1985). One per cent IBA in talc is also successful (Billing

Hansen, 1990), but the solution-dipping method generally seems better. It is recommended that cuttings be treated with a fungicide before 'sticking' them into a rooting medium – often a mixture of peat, sand and grit. Wounding of the cutting bases does not stimulate rooting.

The loss of water from the cuttings should be minimal. This can be achieved using intermittent mist (IM) or fogging systems. The driving force resulting in water loss by the cutting is the difference in pressure between water vapour in the leaves (V_{leaf}) and that in the surrounding air (V_{air}). This difference should be kept as small as possible for success in rooting. IM mainly acts by decreasing V_{leaf} through reduction of leaf temperature, and partly by a modest increase in V_{air} . IM is only applied in the daytime. Under sunny conditions, every 5 min water is supplied for 3–4 s. With overcast weather, mist is applied less frequently, for example, every 10–30 min, but other time regimes are possible. A fog system maximizes V_{air} by raising the ambient humidity. In apple, a fog system gives better results than IM. Fog is supplied when relative humidity falls below 90% and needs automatic continuous control (Billing Hansen, 1989; Hartmann *et al.*, 1990).

Bottom heat (20°C) is not strictly necessary for the rooting of softwood cuttings, but may improve rooting (Nelson, 1976). Suitable air temperatures in the rooting environment range from 20 to 25°C. The rooting process takes from several weeks to several months. When the cuttings are rooted, they should be hardened off by gradually diminishing the air moisture content. Cuttings deteriorate when left under mist too long after they have rooted. The subsequent growth of the cuttings depends on the time of the season when rooting takes place, i.e. the time left for growth after rooting. Climatic conditions and planting distance also play a role. After forcing stock plants from the end of March, planting rooted cuttings in May (northern hemisphere) at 50–70 plants m^2 gave the highest percentages of saleable rootstocks (diameter > 6 mm) – 65% in the case of MM.106 and 45% for M.26 (Billing Hansen, 1990).

Many apple rootstocks have been propagated through softwood cuttings, but the degree of success depends on the cultivar. For instance, MM.106 responds better than M.26 (Billing Hansen, 1989) and M.7 better than M.4, M.9, MM.104, MM.106, MM.109 and MM.111 (Schmadlak, 1969), B.9 is easier than P.2 or P.22 (Grzyb *et al.*, 1989) and, within the Ottawa series, O.7 is the most difficult one (Nelson, 1976). Without forcing stock plants, softwood cuttings are not likely to have much future for commercial rootstock propagation, given the long time period needed to produce saleable rootstocks.

Difficult-to-root apple scion cultivars, such as 'Bramley's Seedling', can also be propagated by softwood cuttings, but only with a combination of three techniques, namely, temporarily covering the stock plants with black polyethylene and then taping and bark-ringing the shoot bases. Covering of the plants is done from bud break until the shoots are 8–10 cm long. Thereafter, 7.5 cm of the shoot base is taped with a band of black polyethylene to keep this part of the cutting etiolated. When, after a few weeks, shoot length reaches 20–30 cm and the etiolation effects of the covering have disappeared and the leaves are green again, the tape is removed and the bark is ringed (4 mm) proximal to the basal blanched stem part. The combination of all three treatments can lead to high rooting percentages and good numbers of roots per cutting (Delargy and Wright, 1978). With rootstocks, simply banding the shoot bases with Velcro (2.5 cm × 2.5 cm) for up to 20 days before the cuttings are collected can also improve rooting percentages and root numbers per rooted cutting – for example, with M.9 and MM.106 rootstocks. The establishment and subsequent growth of M.9 are improved and rotting of the stem bases is diminished by this Velcro band (Sun and Bassuk, 1991). Blanching of non-earthed-up stool shoots with opaque tape is more effective than earthing up, probably because it is done earlier and excludes the light more effectively (Howard *et al.*, 1985).

6.4 Micropropagation

6.4.1 Propagation *in vitro*

Apple rootstock and scion cultivars can also be propagated in the laboratory. The most common method is to use tips or parts of shoots of a few mm to 1 cm in length. These tiny 'explants' are surface-sterilized and cultured in vessels on a suitable medium in illuminated rooms under sterile conditions. The various media used contain mineral salts, a carbohydrate source (sucrose or sorbitol) and a cytokinin, often 6-benzyladenine (BA). The shoots, once established *in vitro*, grow and produce new shoots from axillary buds (Plate 6.7). Shoots are excised at intervals of about a month and placed into a fresh medium for further multiplication. This subculturing can go on for years. When sufficient shoots have proliferated, the small shoots are induced to form adventitious roots (Plate 6.8) on another, cytokinin-free, medium, which should contain an auxin, usually IBA (Jones, 1993). There are several variations and modifications in the media and in the procedures successfully used for apple culture *in vitro* (Lê, 1985; Collet and Lê, 1987, 1988; Hutchinson and Zimmerman, 1987; Pawlicki and Welander, 1994). Rooting can also be stimulated by adding certain thiol compounds to the medium (Auderset *et al.*, 1996). When sufficient roots have been formed, the plants are transferred to pots filled with potting compost or another substrate and brought into a glasshouse for further development. Establishment in the glasshouse also depends on the potting substrate (Lê and Collet, 1991) and can be improved by using a fog installation and elevated carbon dioxide levels (van Telgen *et al.*, 1992). Finally, the young plants are planted in soil outdoors.

Because this propagation method is quite complicated and costly, quicker methods have been sought. An important simplification is to cut out rooting under sterile conditions and to root the shoots directly into the potting substrate after dipping their bases in IBA powder (Simmonds, 1983) or after another short auxin treatment *in vitro* (Auderset *et al.*, 1994). This method, sometimes referred to as 'direct sticking', also

improves establishment in the soil, often a weak point after *in vitro* propagation (Webster and Jones, 1991). The establishment problems are possibly due to the modified root anatomy of roots formed *in vitro* (McClelland *et al.*, 1990), although the stomatal closure of leaves formed on *in vitro*-raised shoots is also often impaired and this can result in their rapid desiccation.

The production of shoots and roots on *in vitro* cultures usually increases with ongoing subculturing. The gradual physiological change during subculturing leading to these improvements is termed 'rejuvenation'. It was assumed that the number of subcultures was important (Webster and Jones, 1989) in this rejuvenation, but later it was shown that the total time spent in culture was the decisive influence (Grant and Hammatt, 1999). Cultivars, but also clones of one cultivar, differ in their suitability for micropropagation, and within a cultivar differences even occur between shoot-culture lines originating from different shoot-tip explants (Webster and Jones, 1989, 1991; Collet *et al.*, 1994).

6.4.2 Practical applicability

To date, micropropagation plays only a very minor role in practical apple propagation. For scion cultivars, this is due to their poor performance in the orchard (Buban *et al.*, 1993), in particular their delayed precocity of cropping (Plate 6.9). Part of this delayed cropping of trees derived from *in vitro* culture may be due to their small size at planting compared with conventionally propagated trees (Webster *et al.*, 1985). Also, self-rooted trees derived from micropropagation can suffer badly from root suckering and burr-knotting. This may also occur when rootstocks originating from micropropagation are used directly as liners for budding with scions. Therefore, the only current practical use of micropropagated material is for establishing stock plants of rootstock clones, i.e. as starting material for cutting hedges, stool beds or layers. For many years, such material produces many more cuttings or liners per plant with improved rooting capacity compared with conventionally

propagated plants, but without the disadvantages of rejuvenation (Navatel *et al.*, 1988; Webster and Jones, 1992; Jones and Webster, 1993; Czynczyc *et al.*, 1994; Grant and Hammatt, 1999; see also Table 6.2).

A short supply of suitable rootstocks and the long duration involved with tree raising have also been stimuli for *in vitro* rootstock propagation and even tree raising. Using such techniques, it is possible to raise a branched tree on a rootstock in as little as 1 year (Hogue and Neilsen, 1991). However, this method requires more skill and equipment than traditional methods and has not been followed up in practice.

If in the future scion cultivars become available that are compact and yield-productive on their own roots, *in vitro* propagation may replace propagation via rootstocks. Preferably, compact cultivars should not have a chimera structure, as is currently evident in some existing spur types, because *in vitro* propagation may result in reversion back to the original more vigorous parent type, so leading to variable orchards. It has been suggested that reversion may be overcome by reculturing the compact type (Zimmerman, 1997). Although, so far, micropropagation has made no great impact on commercial propagation practices for apple, propagation *in vitro* through adventitious regeneration remains of the utmost importance for the understanding of fundamental physiological processes and for aiding new methods of crop improvement via biotechnology (Jones, 1993; Diekmann *et al.*, 1999; Zhu and Welander, 1999).

6.5 Tree Raising

6.5.1 Site choice

In order to achieve the level of growth sufficient to raise high-quality trees in the nursery, it is essential that the soil is of high quality and well drained and that the site has a provision of irrigation. It is also of the utmost importance that the soil has never before been used for apple cultivation. On 'fresh' (virgin) soil the growth level of young trees is much better than where trees have been grown before ('replant sites'). In many areas nurserymen

are still allowed to treat the soil with chemicals against these 'replant problems' and such treatments do improve young tree growth. On light soils, the nematode *Pratylenchus penetrans* (Cobb) Filipjev & Schum.-Stek. is mainly responsible for poor and variable growth and various nematocides are used to control it. On heavy soils, other pathogens are involved in a 'specific replant disease' and other fumigants are needed. However, increasingly approval for the use of soil fumigants is being withdrawn as part of tightening pesticide legislation. Therefore, it is better to avoid replant problems altogether and to secure fresh land for every nursery cycle. Even after fumigation, tree growth on soils previously cropped with apples rarely matches that achieved on virgin soils.

6.5.2 Planting distance

Whatever the method of tree raising that is employed, an adequate distance between the rootstocks in the nursery is needed to allow

good tree development. To facilitate good light interception by the leaves and to ensure an even uptake of water and nutrients by the roots, a square planting system seems better than an extreme rectangular one. Indeed, adequate between-tree distance within the row is important for side-shoot formation ('feathering') and for good tree-stem diameter (Table 6.3). For trees on M.9, a planting distance of 100 cm × 35 cm is ideal on most fertile soils and will produce trees of good quality and at reasonable tree numbers per hectare. For more vigorous rootstocks, increased tree spacings may be needed, but no data are available to support this suggestion.

6.5.3 Rootstock cutting (heading) back and bleeding

Established budded rootstocks are cut back above the bud grafts in the spring following budding. When this is done in winter, trees may develop better than when cutting is done in spring. However, in certain years

Table 6.3. Tree-quality parameters of 'Jonagold' (J) and 'Gloster' (G)^a on M.9 rootstock at various planting distances in the nursery. Rootstocks (6–8 mm diameter) planted spring 1985 at 16 different spacings (combinations of four row and four tree spacings). Budding August 1985. Measurements autumn 1986. (Adapted from Wertheim, 1986a.)

Spacings (cm)	Tree height above union (cm)	Stem diameter 10 cm above union (mm)	Laterals per tree higher than 40 cm above soil level (no.)	Total lateral length per tree (cm)
Within-row tree spacings: data averaged for row distances				
15	121.7	9.4	2.0	41.5
30	124.7	11.0	4.7	147.8
45	125.0	11.2	5.7	202.0
60	125.8	11.9	5.8	207.8
F test	NS	*	*	*
LSD _{0.05}	—	0.7	1.5	72.5
Between-row spacings: data averaged for tree distances				
60	121.9	10.5	4.3	129.5
70	124.1	10.9	5.0	157.2
80	127.7	11.4	4.4	146.9
100	123.0	10.8	4.9	165.8
F test	NS	NS	NS	NS
LSD _{0.05}	—	—	—	—

^aNo laterals with 'Gloster'.

F test: cultivar × distance NS; tree distance × row distance NS; thus 16 tree spacings combined NS, not significant; *, significant ($P < 0.05$).

and on light soils winter pruning can cause severe tree losses due to the 'bleeding syndrome'. Rootstocks may die back or buds may fail to break or, if they do, the shoots may wilt later on, and the rootstock bark becomes spongy or papery. It is assumed that, when the tissues are still dormant, cutting back dehardens the plant. This is dangerous as in spring many frosts may still occur and at ground level temperatures may drop to very low levels. These freezes may easily damage dehardened tissues. Moreover, by pruning, the rootstock stem has become very small relative to the root system. As the sun warms up the soil, roots become active and take up water, root pressure is built up and the cut rootstock may start bleeding from the pruning wound. When the wound is dried out after early cutting, the sap escapes through the rootstock bark. On heavy soil, bleeding is normally not excessive. Compared with light soil, water uptake requires more energy and soil temperatures are not so readily raised. On light soils, therefore, heavier tree losses occur due to early cutting back (van Oosten, 1980a,b). It also seems likely that *Pseudomonas* spp. bacteria may be involved in the damage (Sholberg *et al.*, 1993).

To prevent the 'bleeding syndrome', cutting back of rootstocks is best postponed until after the last spring frosts. However, this leads to smaller trees, because the remaining season available for their growth is shorter. A compromise solution is to cut back neither too early nor too late. In The Netherlands, for those years that experience early bud development, the beginning of March is the recommended time and for years with later bud break the second half of March is preferred (van Oosten, 1980a). Elsewhere pruning times may be different.

Other measures considered beneficial, but not proved, are to make a large wound or to leave a rootstock stump ('snag') at the time of cutting back. In the former case, a slanting knife cut is made starting slightly higher than bud height but at the opposite side of the rootstock, ending about 5 cm above the bud. In the second case, cutting back is done at 10–15 cm above the bud. In both cases, a larger surface area some distance from the

bud union is available for sap loss. Later, the stumps left by both methods are removed directly above the bud. A temporary snag has no negative effects on tree quality. Soil cultivation to a depth of about 10 cm, destroying part of the surface root system, is another suggested remedy. If bacterial infection of the cut surface occurs, sprays with bactericides might alleviate the problem, as will providing a temporary straw cover after cutting back as protection against frosts.

The most radical solution is to completely abandon tree raising with established rootstocks on light soils. Indeed, with snip or interstem tree raising, which starts with bare-root rootstocks, fewer bleeding problems are experienced.

6.5.4 Plant material

The majority of apple trees produced in nurseries are of one of three types: 1-year-old ('maiden') trees, 'snip' trees and interstem trees. One-year-old trees originate from budding on established rootstocks, planted as liners in the early spring. After the rootstock has been cut back in the spring after budding, a shoot rises from the bud graft. Depending on the cultivar, it may or may not form laterals ('feathers') (Plate 6.10). This formation of side-shoots can be induced or improved using various techniques (see section on branching). In autumn, the trees are lifted and sold, either immediately or following an intermediate storage period, outside or indoors. At the time of sale, the tree head is 1 year old and the root system 1 year older. Well-feathered 1-year-old trees have replaced the 2-year-old trees that used to be the only branched trees available from nurseries. The latter were retained in the nursery for a further year when no or few side-shoots were formed in the first year. By cutting the vertical stem at heights varying from 85 to 110 cm, depending on the cultivar, branching was induced.

Snip trees arise from rootstocks planted in spring bearing a graft or a dormant ('sleepy') bud. The scion buds grow out at the same time as buds on conventional maiden trees, but in the first year development is moderate because the roots have not established as well

as on the rootstocks used for the maiden trees, which have been in the ground a year longer. In the following winter, the single stem ('whip') of the snip tree is cut at 50–80 cm above the ground and only the highest bud is allowed to grow out. By then, the root system is established and the terminal shoot grows out so vigorously that, depending on the cultivar, many laterals are usually formed (Plate 6.11). Again, branching treatments may help to improve side-shoot formation. Currently, a cutting back height of 80 cm is preferred for snip trees, especially with vigorous cultivars. This height gives a fairly long trunk, allowing the fruiting laterals that develop from the laterals on the tree following orchard planting to bend down under the fruit weight without the need for premature shortening. In this way, early cropping of difficult cultivars becomes more feasible. The tree head of snip trees is 2 years old. The name snip is derived from the Dutch word 'knipboom'; 'knip' means cut or snip, referring to the cut that is made to the 1-year-old stem.

Interstem trees are made using several methods. Traditionally, interstems are budded on to established rootstocks in late summer. Next year at approximately the same time, the scion cultivar is budded at about 50 cm above the ground on to the interstem. Currently, interstem cultivars are also budded on to bedded rootstocks in late summer or bench-grafted on to bare-rooted rootstocks in late winter. In both cases, the combinations are spring-planted in the nursery for a 2-year production cycle. In the late summer of the first season in the nursery, the scion cultivar is budded at about 50 cm above ground level on to the interstem. With the lower rootstock union at 15 cm, the interstem is usually 35 cm long, but its length may vary according to local requirements. Interstems are used to provide the tree-trunks with resistance to diseases (the Dutch apple cultivar 'Dubbele Zoete Aagt' against a trunk rot caused by *Phytophthora cactorum* (Lebert & Cohn) Schroter) or to freeze damage ('Hibernal' or 'Summerred'). Moreover, interstem trees branch as freely as snip trees and they similarly raise the height of the fruiting laterals. In many parts of the world interstems or interstocks are used to control

tree vigour. In environmental (soil and site) conditions unsuited to the use of dwarfing rootstocks, it is necessary to use tolerant and often invigorating rootstocks to ensure tree survival and longevity. This is relevant in many parts of the southern hemisphere where woolly aphid is a major pest of tree root systems. Dwarfing in these situations is achieved by using a dwarfing interstem, such as M.9, together with a tolerant understock, such as MM.106 or MM.111. These interstock trees are raised using similar techniques to those described above.

The cropping level of snip and interstem trees (Plate 6.12) is usually better than that of 1-year-old trees and for all tree types it holds that the higher the number of laterals, the higher the yield in the first years following planting (Wertheim *et al.*, 1995). For this reason, well-branched interstem or snip trees are currently preferred by many apple growers, even though they may be slightly more expensive to purchase. In areas where large well-branched material would suffer from spring droughts and where no irrigation is possible, it might be better to plant less-developed material, which will establish more easily in such conditions.

6.5.5 Tree support

On dwarfing rootstocks tree support in the nursery leads to the production of better trees. Bamboo canes or similar supports are placed into the ground next to each tree in the row at or shortly after bud break. The main shoot is regularly attached to the supports with tape, usually using a special tying apparatus. The support prevents leaning or breakage at the union and contributes to a high growth rate of the shoot leader, an essential condition for feathering (Tromp and Boertjes, 1996).

6.5.6 Trunk cleaning

Shoots may arise from the trunk in positions where they are not wanted. In the final year of the growth of 1-year-old trees, shoots originating lower than 40–50 cm above the soil

are unwanted. If retained and allowed to develop, fruits borne on such branches hang too close to the ground and are thus difficult to pick and prone to rot because soil fungi may splash up with soil particles during rain. Laterals that are too low are rubbed away when still only a few centimetres long. By doing this early, wounds are small and heal easily. This measure may slightly favour the formation of higher laterals and has no negative effects on trunk size or tree height (de Groene, 1986). With snip and interstem tree raising, shoots below the preferred terminal shoot are also rubbed away, but in stages, with time intervals between each removal in spring and early summer, to prevent bleeding.

6.5.7 Other types of plant material

Apple-tree raising in containers is not considered an economically viable option, because it requires a great deal of attention to detail and is expensive and establishment is more difficult (Wertheim and de Groene, 1988; Wertheim and Wijsmuller, 1988; Wertheim, 1989). Similarly, planting of 'half-finished' products directly in the orchard cannot be recommended. Bench grafts or rootstocks with dormant scion buds give disappointing yields compared with finished trees and result in more tree losses and tree-to-tree variability (Bootsma and Baart, 1990).

6.6 Budding and Grafting

In commercial nurseries, apple trees are most often produced by either late-summer budding of scion cultivars on to rootstocks in the field or by bench grafting them on to bare-rooted rootstocks indoors in late winter. Two systems of budding may be used to raise trees. In the first, budding is done on to established rootstocks planted in the preceding dormant season and in the following year the bud develops into a 1-year-old tree ('maiden tree'). In the second system, budding is done on to closely planted bedded rootstocks, which are then dug up in autumn (with what are called 'sleepy'

buds), stored, planted out in the nursery in the following spring and raised as snip trees during the next two seasons. Bench grafts that are made indoors during the late winter are planted out in spring and the trees also develop during the next two growing seasons, as for snip trees. The longer period needed for snip trees is due to them making only moderate scion development ('whips') in the first year. This is because the rootstocks are not sufficiently established in the nursery in the first spring. Budding makes more economical use of scion propagation material than grafting and is more popular currently than grafting. Where rootstocks have failed to reach sufficient size for budding in the previous summer, trees are occasionally grafted in early spring outside in the nursery. In the past, when buds that were inserted in rootstocks during the summer failed to 'take' (failed to heal and form a viable union with the rootstock) they were grafted in the subsequent spring. This is not recommended, however, as poor bud take is usually indicative of graft incompatibility, virus infection or some other health problem with the stock or the scion.

Budding and grafting are also used in top-working established trees in the orchard. Top grafting (also termed top working or frame working) has recently become quite popular in the UK as a method of rapidly converting an existing orchard over to one or more new scion cultivars. Significant yields are produced several years in advance of planting new trees using this technique and the costs of converting the orchard are much less than when purchasing new trees. The technique is only to be recommended on trees that were known to be virus-free at the time of planting the original orchard. Unlike stone fruits, where viruses are transmitted easily in pollen, apple viruses seem to be transmitted only by budding and grafting, and healthy orchards generally remain clean throughout their lives. Top- and frame-work grafting of apple trees is carried out during the dormant season using healthy, virus-free scion wood. Details of the various techniques used are given in Garner (1979) and Hartmann *et al* (1990).

6.6.1 Bud wood

In budding, a piece of stem and bark of a scion cultivar carrying one bud is inserted into the stem/bark of a rootstock. Bud wood is taken from the middle part of current-year shoots obtained from mother trees of a certified healthy source. Shoots used should possess healthy leaves and well-developed buds. This rules out the use of the succulent shoot tip as well as the woody basal part. Shoots with flower buds are discarded. After collection, all leaf blades and stipules are quickly removed to prevent dehydration. Leaf petioles are usually left intact at this deleafing to facilitate bud insertion and as a later indicator of success or failure of bud take. With successful bud take the petiole drops off, whereas it withers and stays on where a bud does not unite with the rootstock. However, petioles can also be removed with the blades, because the above advantage is considered of minor importance by some nurserymen.

After leaf removal, the shoots of bud wood should be used as soon as possible. In cool and moist conditions, they can be stored for up to 1 week, but it is better to always use freshly harvested material where possible. As long as well-developed buds are used, the bud origin on the shoot is of no consequence for bud take or tree quality (Smith *et al.*, 1962). To smooth peaks in demand for labour needed for budding, bud wood can be stored for up to 4 weeks at 2°C. Longer storage gives lower bud take (Versteegen, 1989). In the field, bud sticks should be kept fresh by keeping them moist and cool.

6.6.2 Rootstocks, budding height and site

To be suitable for budding, rootstocks should be neither too thick nor too thin. In the case of M.9, suitable basal-diameter classes at planting are 5–7 mm and 7–9 mm (van Oosten and de Groene, 1980). Preferably, the two classes are planted in separate blocks as they may render trees of different quality. Budding is done at least 10 cm above ground level to prevent scion

rooting later in the orchard, but 15 cm is a better standard. For special purposes, such as increasing dwarfing or alleviating problems of disease, budding height is higher. For growth control of vigorous scion cultivars, even on dwarfing rootstocks, such as M.9, heights of 25–35 cm are often preferred. Also, with 'Cox's Orange Pippin', a cultivar very susceptible to *Phytophthora* trunk rot, budding height is at least 30 cm. In this way, the soil-borne fungus cannot reach the trunk of the scion cultivar by the splashing of soil particles containing the pathogen during heavy rains.

It is usually irrelevant which side (orientation) the bud is inserted into the rootstock stem, but in windy conditions budding on the windward side reduces chances of the buds being pushed out by strong winds. However, when shoots are tied to supporting bamboo canes, this is not necessary. When budding is done on over-row carts, to make the work less tiring for personnel, buds are inserted in the same direction as the row because the rootstocks are bent over that way.

6.6.3 Budding and grafting methods

Two techniques of budding, T- and chip budding, are used for propagation of apple trees. In both techniques it is essential to achieve effective joining of the cambial layers of the scion bud and the rootstock and to prevent desiccation.

In T-budding, a T-shaped incision is made in the rootstock rind at the time in summer when the bark easily slips from the underlying xylem to facilitate bud insertion. In the northern hemisphere this happens from late July till early September. An upper transverse cut is made first, about 1 cm long. A second, vertical cut of about 2.5 cm is made upwards, such that it meets the first one at its middle point. The bud graft is a thin, narrow, oval-shaped piece of bark including a central bud and with some wood tissue on the inside. Holding the bud stick by the upper end a cut is made beginning about 1 cm below a bud. Thereafter, the knife is moved shallowly upwards beneath the bud

to about 2.5 cm above it. The shield is then torn from the stick leaving a bark strip that facilitates insertion. After insertion, this strip is cut away and the two rootstock bark flaps are bent back over the bud graft (Anon., 1963; Hartmann *et al.*, 1990).

In chip budding, an oval shield with the central scion bud replaces an exactly similarly shaped piece of bark removed from the rootstock and consequently the cambia of the two partners usually match very well (Plate 6.13). Both chips are cut out in a similar manner. On the bud stick, the first cut is made 0.5 cm below the bud down into the wood at an angle of 30–45° to a depth of approximately one-quarter of the rootstock diameter. A second cut starts about 2.5 cm above the bud and goes inwards and downwards behind it until it meets the first cut. The sequence of making the cuts may be reversed. In the rootstock a similar chip is removed in a similar manner. The cambia of bud stick and rootstock should be opposite each other, at least at one side of the union. The good juxtaposition of the cambia of scion and rootstock in chip budding leads to a rapid fusion and good bud take. For chip budding it is not strictly necessary for the rootstock bark to slip easily at the time of budding; this gives slightly greater flexibility and a longer time period during which budding can be undertaken.

In lifting the bark from the rootstock in T-budding, the cambium zone remains attached to the inside of the bark. Therefore, the rootstock cambium cannot quickly match with the scion-bud cambium (Mosse and Labern, 1960). This has consequences for their coalescence and may affect bud take and tree quality adversely. For these reasons, chip budding seems the better method. Compared with T-budding, chip budding often resulted in better bud take, less freeze damage of buds and more developed and uniform trees (Howard, 1974; Howard *et al.*, 1974; Skene *et al.*, 1983). However, in a few studies no benefits of chip budding have been shown (Meiß, 1985). A minor drawback of T-budding is that spores of the fungus *Nectria galligena* (Bres.), which may be present on the outside of the bud graft, can be introduced into the rootstock and fruit-tree

canker may develop. However, in hot areas T-budding might be the better procedure, because the protective bark slips decrease the risks of desiccation (Hartmann *et al.*, 1990). Desiccation is the major problem with chip budding and it is only since the advent of polythene or rubber tying materials that the popularity of the technique has increased; chip budding was rarely successful when only raffia bud ties were available. Commercially, both methods of budding are currently used successfully. The fate of bud take can be non-destructively determined by magnetic resonance imaging (Warmund *et al.*, 1993) – useful in cases of new scion–rootstock combinations where graft incompatibility may be suspected.

6.6.4 Tying and after care

Tying must be done very soon after budding, either with rubber bands, which deteriorate (break down) after a few weeks so that the thickening rootstocks are not girdled, or alternatively with 1 cm wide plastic strips of polyvinyl chloride (PVC) film (Plate 6.14). This latter material is elastic, moisture-proof and transparent, allowing inspection, but it does need to be cut after the buds have healed. This is done with a superficial knife cut made to the plastic on the side opposite to the bud. Rapid and complete cover of the wound and bud may help to prevent damage by the red-borer fly (*Thomasiana oculiperda* Rubs). In areas where this pest is not a problem, other ties may need to be used.

It is very important that the binding material does not girdle the rootstock, as this will delay growth and lower tree quality. For the same reason, budding should not be done too early in the season when much rootstock stem thickening still has to occur. Moreover, early budding can stimulate the bud grafts to grow out shortly afterwards. This is unwanted as the little shoots can easily be damaged by winter freezes. In the northern hemisphere, most thickening occurs in July and August. Hence, budding in the second half of August is better than in July (Smith *et al.*, 1962).

After budding, the rootstock is not pruned until next spring to keep the bud graft dormant. In spring, the rootstock part situated above the bud is cut off either completely or in stages.

6.6.5 Bench grafting

Bench grafts are made indoors during the winter season. The main method used is the whip-and-tongue graft (Garner, 1979, Hartmann *et al.*, 1990). In order to economize on costs for propagation material, the grafts are short, bearing only two buds. With whip-and-tongue grafting, the diameter of the stem of the scion and the rootstock should be about equal. When the rootstock is thicker, side-grafting is used, although it is known that the union of the two partners is less strong than with a whip-and-tongue graft. After grafting, the two partners are firmly tied together with a plastic strip and the apical end of the graft is sealed with grafting wax. Bench grafts can be planted out directly but, when soil conditions do not permit this, storage at about 2°C under high humidity, to prevent dessication, is necessary.

6.7 Branching

The vigorously growing vertical shoot of the apple scion (the central leader) that arises from the bud, may or may not form sylleptic shoots, or 'feathers'. For a high-quality tree, the presence of a good number of feathers is desirable, because they form flower buds in the year following orchard planting and enable the tree to bear fruit in the second year. The more feathers, the higher the yield in the first years (van Oosten, 1978; Wertheim, 1981), and all nursery efforts should be directed towards raising feathered trees.

Cultivars vary greatly in their tendency to form sylleptic shoots. Some hardly feather at all, while others do so very freely. There is also a year-to-year effect on feathering, pointing to a role of environmental conditions in the induction and development of feathers. Indeed, air and soil temperature and humidity have great effects on sylleptic

shoot growth (SSG). Controlled-environment experiments have shown that an 18-week period with air temperatures of 25°C, starting at bud break, greatly enhances SSG, compared with a similar period at 15°C. When a temperature of 25°C was given for 6 weeks following a similar period with low temperatures, SSG was also greatly favoured, whereas 15°C in the second 6-week period had no effect (Tromp and Boertjes, 1996). The higher the soil temperature in the range 7–28°C during the growing season, the more laterals are formed (Tromp, 1992a). SSG was strong when soil temperature was 12°C during the first 6 weeks after bud break followed by a similar period of 22°C (Tromp, 1996). High humidity also favours lateral formation (Tromp, 1992b). A high humidity (90%) given in the first 6 weeks after bud break promoted SSG at 22°C soil temperature, but not at 12°C (Tromp, 1996). The interaction of external factors means that feather formation in the nursery will vary depending upon seasonal conditions. It also follows that some climatic conditions or sites are more favourable for the raising of feathered trees than others.

It has long been assumed that the apex of the parent shoot inhibits lateral growth by auxins produced in the tip, which are then transported basipetally. However, the background to lateral-shoot inhibition is more complex than this (Cline, 1994). It is possible that competition for water and nutrients is involved, for when these are limiting only the main shoot grows. Whatever the cause, SSG in apple mainly occurs when the growth rate of the main shoot is highest (Tromp, 1996).

6.7.1 Manipulation of branching by hand

Removal of the growing tip induces lateral-shoot formation, but tipping is not a good technique, because it induces laterals that grow out with very narrow branch angles (Cody *et al.*, 1985; Jarassamrit, 1989). In the orchard, narrow-angled branches can break off easily under a heavy fruit load and narrow crotch angles may also become infected by *N. galligena* (Bres.), leading to fruit-tree

canker. Narrow angles also arise when the growing tip is killed by use of too aggressive chemical branching agents. In contrast, when a shoot tip is gently reduced in growth activity, well-positioned laterals with broad branch angles arise. This gradual slowing down of the speed of growth of the leader can be achieved manually by removing the leaf blades from the actively growing tip, leaving the actual growing point intact. A single removal of leaf blades exerts an effect, but repetitive treatments at 7–14-day intervals are more effective (Table 6.4). It is important that all young leaves that are still light green in colour are removed completely. Removal of only parts of the young leaves is not effective (Wertheim, 1978a), nor is taking away mature leaves under the shoot apex (Table 6.4). The most effective treatment of the trial summarized in Table 6.4 was a combination of three successive removals of young apical leaves plus a 'Promalin' spray. This produced 8.4 feathers per tree compared with 2.6 for the untreated control.

After tipping and removal of the apical meristem, shoots arise under the wound, but with leaf removal as described above they arise both below and above the height of treatment (Wertheim, 1978a,b). Taking away leaf blades can easily and quickly be carried out by casual labour. In the case of some difficult-to-feather cultivars, some nurserymen deleaf up to six times in a growing season.

6.7.2 Manipulation of branching by chemicals

A chemical branching agent applied once can have a beneficial effect on feathering (Table 6.4), but mixtures applied once or repeated sprays with the same compound or with two different chemicals are usually more effective. Effective chemicals are: 'M&B 25,105' (propyl 3-*t*-butylphenoxy acetate), BA, GA₄₊₇ (gibberellins A₄ + A₇), and a mixture of 50% each of BA and GA₄₊₇, such as 'Promalin'. All chemicals act better when

Table 6.4. Results of a branching trial with 'Red Boskoop' on M 9 rootstock. Sixteen treatments were compared, namely, one spray of 'Promalin' when the leader was 65 cm in height at 1000 p.p.m. each of BA and GA₄₊₇ (P); stripping the apex one, two or three times at 10-day intervals of all young leaves (commencing when leader height 65 cm) (A); and stripping the sub-apical zone only once (45–65 cm above the ground) when the leader height was 70 cm (SA) and all combinations (data not shown). (Adapted from Wertheim *et al.*, 1989)

Treatment ^a	Tree height above union (cm)	Stem diameter (mm) ^b	Feathers per tree > 10 cm (no.)	Average feather length (cm)
-P	139.5	14.2	4.0	22.1
+P	136.4	14.6	7.3	24.2
F test	NS	NS	***	NS
LSD _{0.05}	—	—	0.7	—
-SA	137.4	14.4	5.7	22.4
+SA	138.6	14.5	5.6	23.9
F test	NS	NS	NS	NS
LSD _{0.05}	—	—	—	—
A 0x	139.9	14.1	4.7	15.9
A 1x	136.4	14.1	5.5	21.6
A 2x	137.9	14.6	5.9	27.5
A 3x	137.6	14.8	6.7	27.6
F test	NS	NS	***	*
LSD _{0.05}	—	—	0.9	8.8

^aSee table title.

^b20 cm above union

F-test interactions P × SA, P × A and A × SA not significant; thus 16 treatments combined
NS, not significant; *, significant ($P < 0.05$); ***, very strongly significant ($P < 0.001$)

applied with a wetting agent (Wertheim, 1978a,b; Gerhard, 1984; Cody *et al.*, 1985; Jarassamrit, 1989; Wertheim *et al.*, 1989; Volz *et al.*, 1994; Wertheim and Estabrooks, 1994).

As with manual treatments, branching agents only have their beneficial effects if applied to a vigorously growing shoot. It is sufficient to treat only the top 25 cm of the shoot, although 'Promalin' also acts when applied to mature leaves and to lateral buds (Gerhard, 1984). Applications can start at a leader height of 45 cm, but this may induce laterals to form too low on the leader, for they arise a few decimetres below and above the height of treatment (Wertheim, 1978a). After eight weekly sprays with 200–400 p.p.m. BA treatments on 'Red Boskoop', starting when the leader was 35 cm above the budding height (50 cm above the ground), the zone of lateral emergence was enlarged from 31–70 cm to 31–120 cm above the union (Wertheim and Estabrooks, 1994) (see Plate 6.10). With single sprays, best results are obtained when shoot tips are approximately 65–70 cm above ground level at the time of treatment. Sequential sprays may begin at a lower leader height – for example, 50 cm. If the growth level is insufficient, only thick lateral buds may arise, but no lateral shoots. Although the treatments do not affect the trunk size, they may reduce final tree height, but this effect is normally not of commercial importance.

Successful chemical treatments are achieved using 500–1000 p.p.m. 'M&B 25,105' followed 2 weeks later by 4% 'Promalin' (–720 p.p.m. of both BA and GA₄₊₇) (Gerhard, 1984). Alternatively, a mixture of 1000 p.p.m. 'M&B 25,105' + 250–500 p.p.m. 'Promalin', or a spray of 1000 p.p.m. 'M&B 25,105' followed 1 week later by 500 p.p.m. 'Promalin' (Cody *et al.*, 1985) can also be effective. Mixtures of 1000 p.p.m. BA and 1000 p.p.m. GA₄₊₇ or sequences of these two hormones with 2-week intervals are also successful (Volz *et al.*, 1994). Also very successful were one or two sequences of BA and GA₄₊₇, each at 1000 p.p.m., with 2-week intervals, as were two successive applications of 'Promalin' with a 2-week interval between, or 1000 p.p.m. of both hormones. The number of feathers is sometimes spectacularly

raised – for example, from 4.0 in control trees to 15.9 per tree after eight weekly sprays with 400 p.p.m. BA (Wertheim and de Groene, 1993). Results differ per cultivar; in one nursery where four or six sequential weekly sprays with 150, 300 or 600 p.p.m. BA were evaluated, 'Elstar' reacted best to four sprays of 300 p.p.m. BA, 'Cox's Orange Pippin' to four times 300–600 p.p.m., 'Delcorf', 'Golden Delicious' and 'Jonagold' to six sprays with 300 p.p.m., and 'Red Boskoop' to six sprays with 600 p.p.m. With all the cultivars, spectacular increases in numbers of laterals were obtained and subsequent orchard performance was not negatively affected (Wertheim and de Groene, 1995). Eight sprays of 200–400 p.p.m. BA may diminish the flower-bud formation that sometimes occurs on 1-year-old trees (Wertheim and Estabrooks, 1994). This may be regarded as an advantage, as the trees can establish more easily without fruits being formed in the planting year. An example of the possibilities of using a series of BA sprays is presented in Table 6.5. A combination of repeated manual deleafing and one 'Promalin' spray proved slightly more effective than 'Promalin' alone (de Groene, 1990).

For success in branching, not only the vigour of growth is important; the environment must also be favourable. Weather factors cannot be influenced, but other factors can. Only soils of excellent quality should be chosen, rootstocks at planting time should be of adequate size and within-row planting distances ample to allow for good lateral growth (Wilson and Jarassamrit, 1994). At a planting distance of 100 cm × 10 cm, feathering of several apple cultivars was rather poor, although improved by BA and GA₄₊₇ combinations and sequences (Volz *et al.*, 1994).

There is a reluctance to use branching agents among nurserymen, because of inconsistent results and/or lack of demand for feathered trees (Miller, 1988). Given the effects of environmental factors, inconsistency is to be expected, although this can be reduced by repeated treatments (Table 6.5). Reluctance to induce feathering may also be based upon the more difficult handling of feathered trees during harvest, storage and

Table 6.5. Results of a branch induction trial with 'E star' on M 9 rootstock. The first 'Promalin' spray was applied when the central leader was 70 cm high (55 cm above the union) at 1000 p.p.m. of BA and GA₄₊₇. The second spray was applied 2 weeks later. The BA spray was applied one, two, four or eight times at weekly intervals at the concentrations shown.

Treatment ^a	Tree height from union (cm)	Feathers per tree > 10 cm (no.)	Spurs per tree < 10 cm (no.)	Average feather length (cm)	Total per tree ^b (cm)
Control	127.6	4.3	1.6	32.8	284.8
1× 'Promalin'	131.5	6.9	1.6	37.8	389.8
2× 'Promalin'	127.5	6.5	2.4	40.5	391.8
1× 200 p.p.m. BA	131.1	6.5	1.6	37.5	368.1
2× 200 p.p.m. BA	125.0	6.1	1.6	38.9	365.5
4× 200 p.p.m. BA	125.5	6.5	1.3	46.8	435.3
8× 200 p.p.m. BA	125.4	7.4	1.4	43.6	444.5
1× 400 p.p.m. BA	124.9	5.1	2.9	44.2	360.4
2× 400 p.p.m. BA	129.5	6.0	0.9	43.4	396.0
4× 400 p.p.m. BA	125.3	7.1	1.8	42.0	432.6
8× 400 p.p.m. BA	121.0	9.0	2.6	38.3	471.9
1× 800 p.p.m. BA	129.3	6.4	2.3	41.9	410.4
2× 800 p.p.m. BA	127.5	7.9	0.5	44.7	478.0
4× 800 p.p.m. BA	119.6	7.6	3.0	36.5	403.5
8× 800 p.p.m. BA	124.3	13.0	3.3	37.7	617.1
F treatment	**	***	**	**	***
LSD _{0.05}	5.4	1.7	1.3	6.4	71.9

^aApplied to 15 cm apex.

^bFeathers + spurs + tree height.

, Strongly significant ($P < 0.01$); * very strongly significant ($P < 0.001$).

transport. Although an understandable reaction by the nurseryman, fruit growers should insist on the supply of well-feathered trees.

With snip and interstem trees the chemical approach to feathering is more difficult, since, at the application height used with 1-year-old trees, the young shoots are still too short and can be easily damaged (Wertheim, 1986b). In this instance, applications, if necessary, should be made later when the shoots are still actively growing but also have a sufficient number of mature leaves.

6.8. Defoliation And Digging Up (Lifting) Trees

It is customary to dig up apple trees from the nursery in autumn, after all shoot growth has stopped and most leaves have abscised. Trees with leaves still present desiccate and

are damaged after lifting. In areas where cold nights in early autumn prevail, natural leaf abscission occurs satisfactorily with most cultivars. However, in maritime climates with mild autumns coupled with relatively warm nights, some cultivars do not shed their leaves easily. In these cases, laborious hand defoliation is needed before trees are lifted. Many efforts have been made to find safe chemical defoliants. Ideally, they should not damage the tree and not adversely affect growth in the next season (Miller, 1988). Ethephon, for example, can induce leaf abscission in apple but with the concentrations needed, growth in the planting year may be reduced, and this is highly undesirable. Copper chelate has in recent years emerged as a reliable defoliant for apple. Depending on the cultivar, one or two sprays with 1–2% of a 9% copper-chelate product plus a wetting agent, applied at the

time that some signs of autumn leaf discoloration and/or some natural leaf drop has begun, induce good defoliation without any subsequent damage. In north-western Europe, this means an application somewhere between mid-September and the end of October (Wertheim, 1984; Faby, 1989). However, its use is only possible in countries where it is registered (approved) for use. In the USA, a combination of ethephon (150 mg l⁻¹), the surfactant 'Depeg' (0.5%) and 'Alanap', the sodium salt of N-1-naphthylphthalamic acid (200 mg l⁻¹), applied in October, showed promise in defoliation studies with apple, but this mixture requires further testing before it can be widely recommended (Larsen and Higgins, 1999).

Tree lifting from the nursery, which involves undercutting the trees, has been largely mechanized, for which tractor-drawn or self-driving machines are used. The trees are undercut with a u-formed knife, lifted from the soil by metal fingers, clasped between two upward-moving rubber conveyor belts, which shake to remove the soil from the roots, and transported to a pallet, where people lay them carefully in a horizontal position. With each layer of trees the

root systems are laid in an opposite direction. A few people can lift 1 ha of trees day⁻¹, even from heavy, moist, clay soil. Tree handling during lifting should proceed carefully to prevent breakage of laterals. After lifting, trees can either be shipped directly to customers or stored until delivery in the spring. Trees can be clamped ('heeled in') outside in bundles situated in a cool, sheltered place with their roots well buried into the soil and protected against rodents by chicken-wire. A safer option is to store the trees indoors in rooms with high humidity at a few degrees above 0°C. Under no circumstances should trees be stored in rooms containing ethylene in the air – for example, emanating from fruit or residual ethylene impregnating store walls after fruit storage – as this leads to reduced bud break on the trees in the spring.

Note

Neither the authors nor their research institutes can accept any liability for loss, damage or injury resulting from the application of any concept or procedure in or derived from any part of this chapter

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7 Flowering, Pollination and Fruit Set and Development

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Flowers are the 'raw materials' for fruit production. Therefore heavy flowering is essential for economic success. But, unlike the situation with floriculture crops, flowers alone are not sufficient. They must set fruit and the fruit must mature and be of sufficient size and quality to be marketed at a profit. This chapter describes the flowering process in apple, how flowers develop into fruits, and how fruits grow and mature.

7.1 Juvenility

Seedlings, whether of herbaceous or woody plants, must pass through a juvenile period before they are capable of flowering. In herbaceous plants this may require a few weeks; in most trees it requires from 1 to 20

years, depending upon species. This creates a problem for apple breeders, who often must wait for 7–9 years before being able to see the fruits of their labours. Treatments that stimulate flowering in mature tissues, such as ringing of the bark (see below), have little or no effect on seedlings until they reach 'ripeness to flower'. Grafting scions from seedling trees into bearing trees can hasten flowering, but the time gained is only a few years. Another method used by breeders is growing the trees as single stems. Flowering can be induced in the second year in some cases, but only buds near the top of the tree flower; there appears to be an effect of 'distance from the roots', suggesting that inhibitory compounds (gibberellins (GAs) ?) produced in the roots move up the stem and prevent flowering. If the distance between roots and buds is sufficient,

the concentration of these compounds is too low to be inhibitory. This hypothesis is questionable, however, because buds taken from a juvenile tree will not flower when grafted into the top portion of a bearing tree.

Commercial cultivars are 'mature' (no longer juvenile); the original seedlings were juvenile, but bud wood taken from the mature, upper parts of these seedlings has been used for propagation through many 'generations' of trees. Young trees on seedling rootstocks generally require several years before they form flower-buds. The time required varies with cultivar, 'Golden Delicious' being very precocious and 'Northern Spy' very late in this respect. When young trees are very vigorous, flowering tends to be delayed. Propagation on dwarfing rootstocks reduces the time to flower considerably, with most dwarf trees flowering within 2–3 years.

7.2 Flower Induction, Initiation and Development

Flower induction refers to the change from vegetative to reproductive phase and can be likened to a switch. However, no visible macroscopic or microscopic changes occur in the bud. Most flower induction occurs in early summer, but it can extend into early autumn under some conditions. Initiation begins when the meristem flattens – visible microscopically – and continues as primordial sepals, petals, stamens and pistils form centripetally on the apex and grow into fully formed appendages (Fig. 7.1). Most of the flower parts are present by early autumn, but continue to develop in temperate climates until low temperatures prevent further growth. In such climates, meiosis begins in the anthers in late winter

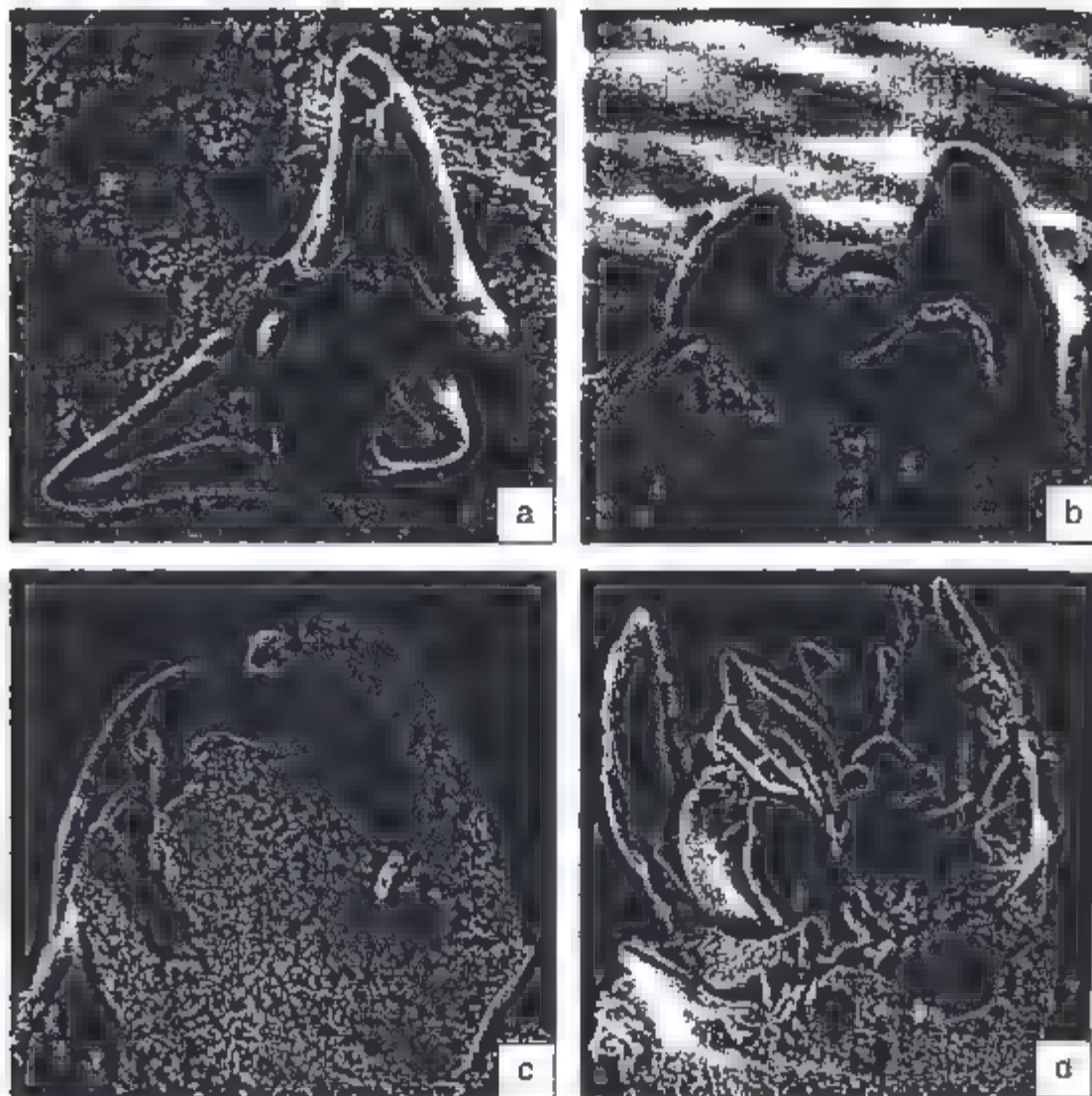


Fig. 7.1. Stages in the initiation of an apple flower at Long Ashton, Bristol, UK, 1974 (Abbott, 1977). Scanning electron-microscope views (a) 1 August – vegetative apex with five leaf primordia, (b) 15 August – apex becoming domed, ridges (floral initials) arising in leaf axil/bract primordia, (c) 21 August – longitudinal section showing 'king' flower at apex, (d) 19 September – five sepals forming on the uppermost lateral flower initial (subtending leaves and 'king' flower removed)

In most fruit-growing areas buds become dormant in late summer/early autumn and winter chilling is necessary to permit renewed growth the following year (see Chapter 10). Weinberger (1950), working in California, used the cumulative number of hours at or below 45°F (–7.2°C) as an indication of the amount of chilling received by peach trees. Although this model has been used at higher latitudes, temperatures below freezing have very little or no effect in breaking dormancy. A model developed by researchers at Utah State University (the 'Utah model') can be used to predict response in areas with colder winters (Richardson *et al.*, 1974). Temperatures between 0 and 15°C are effective, with maximum response at 6–7°C, where 1 h of chilling equals 1 'chill unit' (CU). Temperatures > 16°C have detrimental effects, reducing the response to previous chilling. This model works well in the temperate zone, but is less useful in the subtropics. In these warmer areas the 'dynamic' model (Erez *et al.*, 1988) is a better predictor of response. This model assumes that chilling is accumulated in units and, once such a unit is acquired, high temperature cannot nullify its effect.

Cultivars differ in the amount of chilling necessary to break dormancy. Some (e.g. 'Anna', 'Dorsett Golden') require as little as 250–300 CU and can be grown in the subtropics, whereas others (e.g. 'McIntosh') require much more chilling (1000–1600 CU) and can only be grown at higher latitudes of the temperate zone. If chilling is insufficient, both vegetative and flower buds are retarded in development and cropping is reduced. Exceptions to the requirement for chilling occur in some regions of the tropics, as in Indonesia, where defoliation soon after harvest induces bud break, resulting in two crops per year (Edwards and Notodimedjo, 1987).

Abbott (1977) reported that 20–24 nodes must develop before apple flowers can be initiated. Although studies with potted trees had suggested that flower 'quality' (– ability to set fruit) was optimum when initiation occurred at a specific time, Abbott observed little difference in time of initiation under field conditions. Others have suggested that,

if vigour is excessive, the optimum number is exceeded; if vigour is too low, too few nodes are formed and, in either case, shoots fail to form flower buds.

Flower induction can be inhibited by heavy cropping, some cultivars (e.g. 'Yellow Newtown', 'Paulared', 'Fuji') being notorious for their 'biennial bearing' habit, although all cultivars exhibit some degree of response to heavy cropping. This can be controlled in most cultivars by early fruit removal ('thinning'), either by hand or with chemicals (see also Chapter 16). In general, fruit must be removed within the first 3 or 4 weeks following bloom for thinning to be effective, response declining as thinning is delayed (Fig. 7.2). The physiological basis for this effect of fruits on flowering has been the subject of much research, but remains to be determined. Apple seeds are rich sources of GAs. These compounds can inhibit flowering when applied to limbs or whole trees, and most of the theories proposed include a role for them in inhibiting flowering. In the facultatively parthenocarpic apple cultivar 'Spencer Seedless', seeded fruits inhibit flowering, whereas seedless fruits do not, suggesting that seeds do play a crucial role in flowering (Chan and Cain, 1967; Neilsen and Dennis, 2000). However, few such cultivars exist, and the evidence for the role of seeds in related species, such as pear (*Pyrus communis* L.), is more controversial (see Dennis and Neilsen, 1999; Weinbaum *et al.*, 2001).

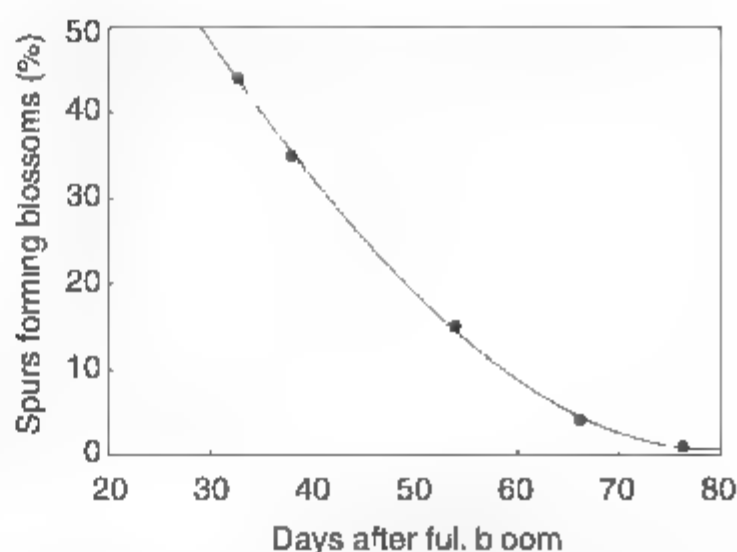


Fig. 7.2. Effect of time of thinning 'Yellow Newtown' apple fruits, to leave one fruit per 70 leaves, on flowering the following year (Harley *et al.*, 1942)

Environmental factors also affect induction and initiation. Although photoperiod plays little or no role in flowering of apple under field conditions, solar radiation is important. Flowering is heavier in well-exposed sections of the tree and in trees in areas with high solar radiation, such as Washington State and California. Experiments with artificial shading have indicated that flowering is reduced whenever the light level is reduced below 30% of full sun (Fig. 7.3). Pruning to open the tree to sunlight is therefore encouraged. Young trees

of some cultivars (e.g. 'Empire') have wide crotch angles, which permit better light penetration; others (e.g. 'Delicious') have narrow crotch angles. Leaves, of course, are important for capturing sunlight, and defoliation reduces flower induction/initiation. Leaf injury from insects and disease can therefore reduce flowering. In controlled environments, high temperature can inhibit flowering in some cultivars (Tromp, 1976), but evidence that this occurs under field conditions in the temperate zone appears to be lacking.

Many cultural practices, including ringing or scoring the trunk or scaffold limbs and bending of limbs, favour flower induction. Ringing/scoring is recommended for young trees only when flowering is delayed considerably, as in 'Northern Spy', but bending or spreading limbs to increase exposure to light is a common practice in young orchards (see Chapter 14). Drought conditions tend to favour flower-bud formation, although this is not well documented and some researchers have questioned the relationship. Heavy applications of nitrogen stimulate growth and tend to reduce flower-bud formation. However, limited evidence exists that appropriate timing in applying summer nitrogen can improve flower quality, leading to better fruit set (Williams, 1965; Hill-Cottingham and Williams, 1967).

Some plant growth regulators affect flowering. Tri-iodobenzoic acid can promote flowering in 'Delicious'. Several other compounds, including ethephon (2-chloroethylphosphonic acid) and the growth retardants butanedioic acid mono-(2,2-dimethylhydrazide) (Alar®), 2-chloroethyl trimethyl ammonium chloride (CCC), and paclobutrazol ((1*R*,3*R*)-1-(4-chlorophenyl)-4,4-dimethyl-2-(1,2,4-triazol-1-yl)-1-pentan-3-ol), are effective on numerous cultivars, although neither Alar® nor paclobutrazol can be used commercially in the USA. In contrast, as noted above, GAs inhibit flowering. Plant responses to GAs differ with species and with the particular GA used; for example, GA₄₊₇ is more inhibitory to flowering of apple than is GA₃ or GA₁ alone (Marino and Greene, 1981; Tromp, 1982), and some evidence suggests that other GAs can actually promote flowering (Looney *et al.*, 1985).

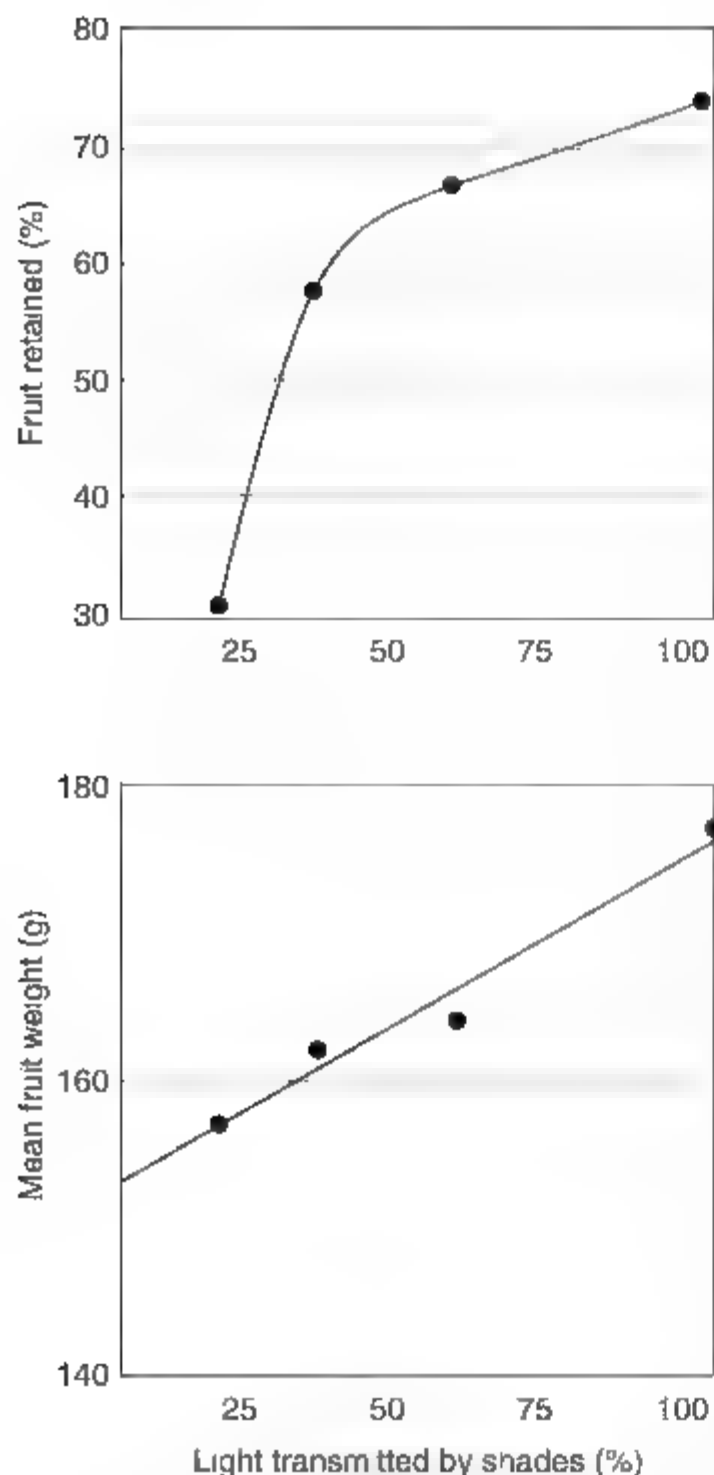


Fig. 7.3. Effects of shading on percentage of fruits retained (top) and on mean fruit weight (bottom) (Jackson, 1975).

7.3 Flowering Habit, Flower Structure

Apple flowers can be initiated in both terminal and axillary buds of both spurs and shoots. Cultivars differ in this respect, some flowering primarily on terminal buds on shoots (e.g. 'Paulared', 'Rome Beauty'), some primarily on terminal buds of spurs (e.g. 'McIntosh', 'Delicious'). Some cultivars rarely or never flower on lateral buds ('McIntosh'), while others often do ('Golden Delicious', 'Gala'). The flower buds are mixed, containing both vegetative and reproductive parts (Fig. 7.4). The flower cluster is a cyme (terminal flower is the most advanced), is terminal within the bud and may contain up to six individual flowers. Further vegetative growth develops from lateral buds proximal to the flower cluster, leading to formation of one or two bourse shoots.

The flower (Fig. 7.5) is epigynous, the ovary being enclosed by non-ovarian tissue (fused base of sepals, petals and stamens or cortex of stem, depending on morphology espoused) that remains attached to the ovary at harvest, giving rise to a 'false' fruit, or pome (Fig. 7.6). A normal flower consists of five carpels, each with two ovules and five sepals, petals and styles. A normal fruit can

therefore contain up to ten seeds. Individual carpels of some cultivars (e.g. 'Northern Spy') may contain more than two ovules. Stamens number approximately 20. The terminal, or 'king', flower is the first to open and gives rise to the largest fruits in 'Delicious' and some other cultivars. Flower clusters in lateral buds open later than do those in terminal buds and generally produce smaller fruit.

7.4 Pollination and Fertilization

7.4.1 Parthenocarpy

Parthenocarpic cultivars of apple exist, but they are of no economic value. The petals are replaced by a second set of sepals and the stamens by a set of ten carpels distal to the normal five. Although pollination leads to seed development, the flowers do not attract bees and most of the fruits are seedless. Commercial cultivars are dependent upon pollination. Although parthenocarpy can be induced with growth regulators, primarily GAs, response is limited and such treatments are not used commercially.

7.4.2 Pollination

Most apple cultivars require cross-pollination to set commercial crops of fruit (i.e. are self-unfruitful) and, even in partially self-fruitful cultivars, such as 'Rome Beauty', 'Jonathan', 'Yellow Newtown' and 'York Imperial', cross-pollination is recommended. Cross-incompatibility (i.e. both cultivars produce viable pollen, but neither will set fruit when cross-pollinated) occurs in very few combinations, such as 'Early McIntosh' $\times$ 'Cortland'. However, triploid cultivars are a more common problem, as their pollen has low viability. The haploid number in apple is 17; hence triploids have 51 chromosomes. Therefore, the chromosomes are unequally divided – or parts of them may occur in the haploid cells – during meiosis. Such cultivars (e.g. 'Winesap', 'Mutsu' ('Crispin'), 'Jonagold') are ineffective as pollinizers for other cultivars. Sports of cultivars, such as the colour sports and spur strains of



Fig. 7.4. Vertical section through an apple flower-bud (diagrammatic). Black appendages – bud scales; stippled – leaves; open – bracts and subtended flowers (apical flower without a bract) (Abbott, 1970)

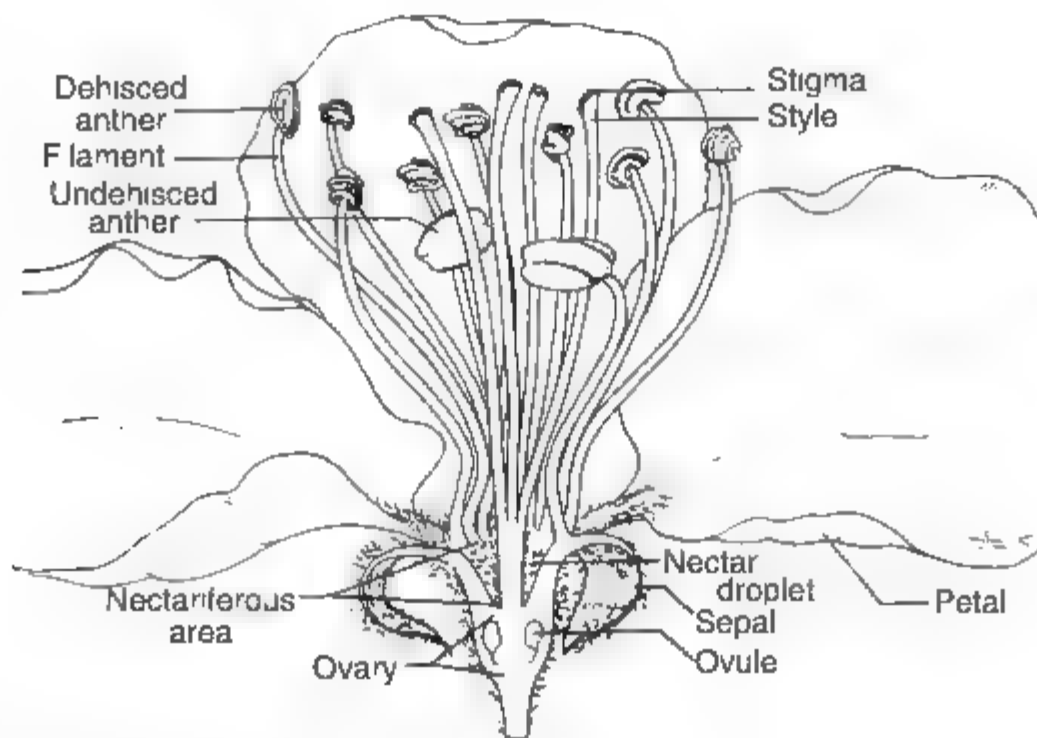


Fig. 7.5. Structure of an apple flower (McGregor, 1976)

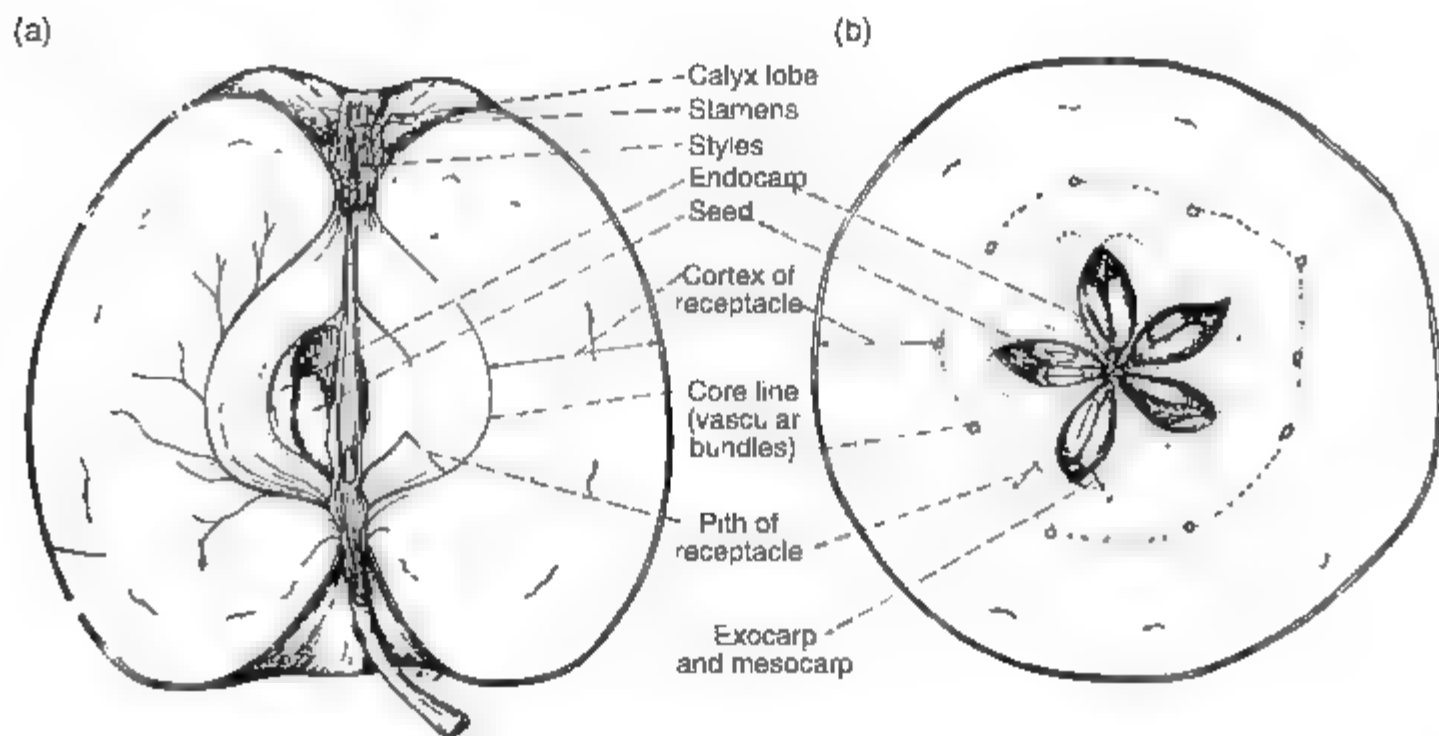


Fig. 7.6. Structure of a mature apple fruit. (a) Vertical section, (b) equatorial section (Robb'ns, 1933)

'Delicious', are not compatible (i.e. are self-unfruitful) with one another, as mutation does not affect the reproductive tissues. In addition to being compatible, pollinizers must bloom at the same time as the cultivar being pollinated and should be annual, rather than biennial, to ensure a supply of pollen each year. Nursery catalogues often contain compatibility charts, providing growers with information as to which cultivars are suitable as pollinizers.

Growers may wish to produce only one cultivar in an orchard and use a minimum number of trees as pollinizers. This can be done by planting pollinizers as every third tree in every third row, providing a pollinizer adjacent to every tree of the main cultivar. To produce even fewer fruits of the pollinizer cultivar, grafts can be inserted on trees of the main cultivar at the same locations. Fruit of the cultivar used as the pollinizer should differ from those of the

main cultivar (e.g. yellow rather than red) to avoid mixing cultivars when harvesting.

Ornamental crab apples can be used as pollinizers in solid blocks of commercial cultivars, generally in orchards propagated on dwarfing rootstocks, with trees planted in hedgerows. This avoids the need for having more than one commercial cultivar in an orchard and simplifies harvest and other practices. The crab apples are planted between trees of the commercial cultivar within the rows and are pruned heavily so that they occupy little space. Three different cultivars are recommended, with bloom times bracketing that of the cultivar being pollinated. They should be planted in each row, as bees tend to travel up and down, rather than across, the rows, and should be offset in adjacent rows for optimum placement. Blossom colour should be similar to that of the commercial cultivar, as individual bees tend to work flowers of a single colour.

If pollen sources are lacking within the orchard, several means are available for introducing compatible pollen. Flowering branches of other cultivars ('bouquets') can be placed in containers with the cut ends in water. Alternatively, pollen can be purchased from commercial companies and used in inserts placed at the entrance of honey bee (*Apis mellifera* L.) hives. Bees exiting the hive unwittingly pick up pollen and carry it to the flowers visited. Another device is available that dusts the insects with pollen as they leave the hive. Pollen can also be 'dusted' on trees by dropping it into the draught created by an air-blast sprayer. Some growers use helicopters to apply pollen from the air, after mixing it with a suitable diluent. However, the 'target' (stigmata of the flower) is very small, thus much pollen is wasted. As a last resort, flowers can be pollinated by hand, but the labour cost is high, even though only one or two flowers in several clusters need be treated.

Apple pollen is heavy and is not carried readily by the wind as is the pollen of some tree species, such as conifers and nuts. The pollen is transferred primarily by insects, especially honey and bumble (*Bombus* sp.) bees. During bloom, prolonged periods of cool weather or rain, which limit bee flight, can be detrimental to fruit set. Fruit growers

rent honey bees from apiculturists during the bloom period, a minimum of four or five strong colonies per hectare being recommended in mature orchards. The bees must be removed from the orchard prior to application of insecticides. For maximum effectiveness, the orchard floor should be mowed to remove flowers (e.g. dandelion (*Taraxacum officinalis* L.)) that may compete with apple blossoms for the bees' attention.

Poor set of 'Delicious' apple has been attributed to the presence of 'basal gaps' between the filaments of the stamens, allowing bees to extract nectar without walking over the top of the flower (Robinson, 1979). Evidence obtained by DeGrandi-Hoffman *et al.* (1985), however, did not support this conclusion.

Timing is important in order for pollination to be effective. Williams (1966) proposed the term 'effective pollination period' (EPP) for the interval during which pollination will result in fertilization. Pollination must occur within a given 'window' (the EPP) in order for the pollen-tube to reach the ovule and for fertilization to occur while the ovule is still receptive (Fig. 7.7). The length of the EPP varies with cultivar, tree condition and temperature. Ovule longevity is shorter follow-

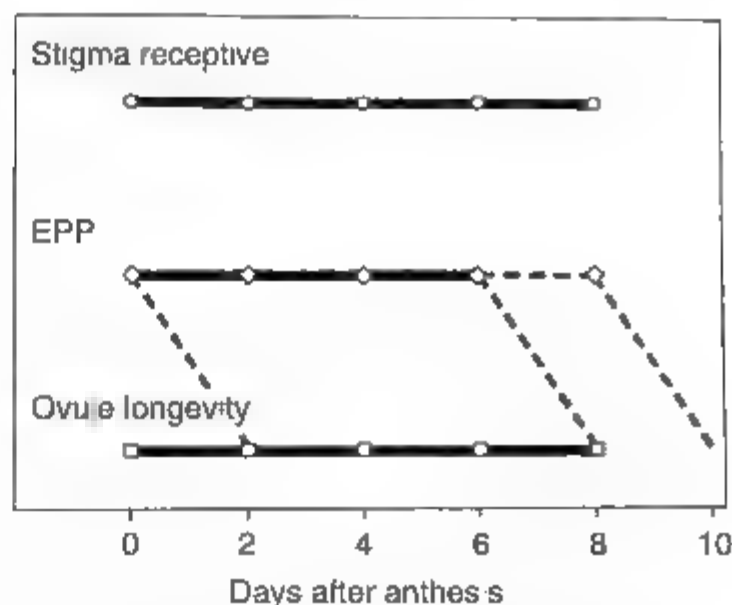


Fig. 7.7. The effective pollination period (EPP). The ovule in this example is receptive for 8 days following anthesis. Pollen-tube growth and fertilization require 2 days. Pollination at any time between 0 and 6 days will result in fertilization; thereafter the ovule is not receptive when the pollen-tube reaches it. Thus, the EPP is 6 days ($= 8 - 2$) (adapted from Williams, 1965).

ing a heavy crop year, but may be prolonged in certain cases, at least, by application of summer nitrogen (Williams, 1965). As the temperature following pollination rises, the pollen-tube grows more rapidly, within limits, but the time during which the ovule is receptive is reduced. Very high temperatures are detrimental to fruit set.

7.4.3 Fertilization

Once compatible pollen grains have been deposited on the stigma, they germinate and the resulting pollen-tubes, each containing three nuclei (tube nucleus and two generative nuclei), grow down the style into the ovary. One tube enters the micropyle and penetrates the ovule (Fig. 7.8), where it ruptures, releasing the two generative nuclei. One of these unites with the egg cell to produce the diploid zygote and one unites with the two polar nuclei in the embryo sac, producing a triploid nucleus. The zygote divides rapidly to produce the embryo, while the triploid nucleus divides to form a free-nuclear, liquid endosperm (Fig. 7.9).

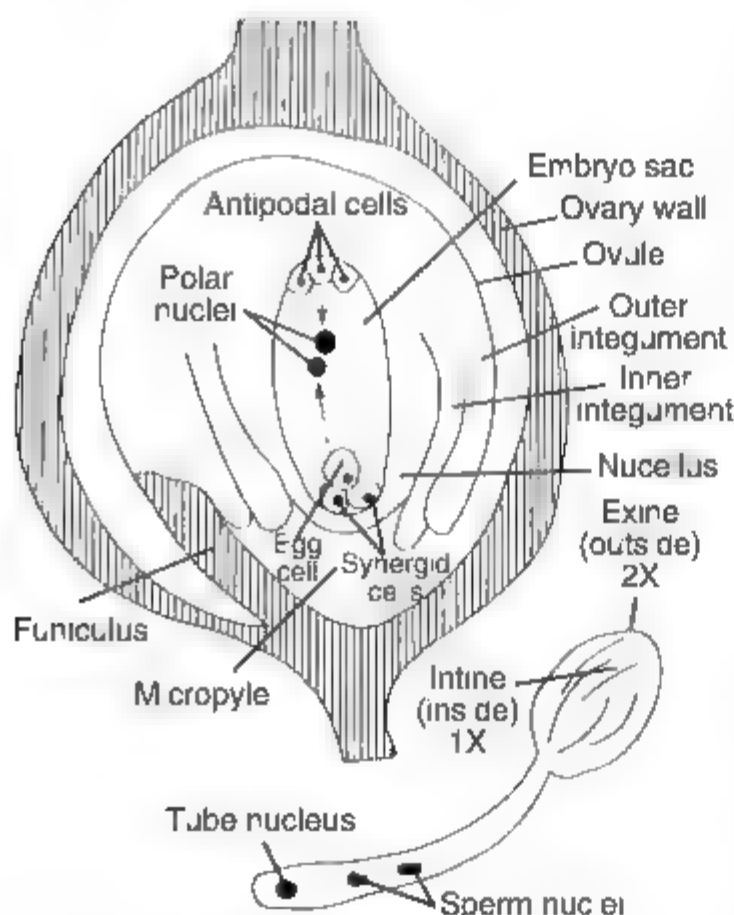


Fig. 7.8. The process of fertilization (diagrammatic) (Dennis, 1996)

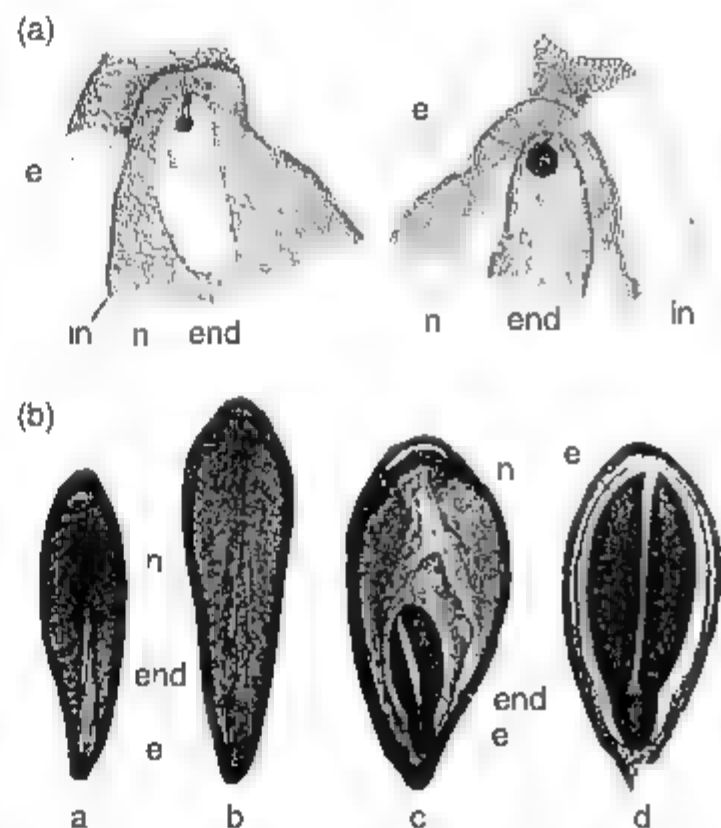


Fig. 7.9. Stages in apple seed development. (a) Endosperm 24 (free-nuclear) and 31 days (cellular) after fertilization. (b) Embryo and endosperm development at (a) 24, (b) 31, (c) 45 and (d) 76 days after fertilization. in, integument; n, nucellus; end, endosperm; e, embryo (Luckwill, 1959)

7.5 Fruit Development

Soon after fertilization occurs, the ovary and surrounding receptacle tissues begin to grow and the fruit has set. However, flowers in which fertilization did not occur soon fall and many developing fruits abscise before reaching maturity. An abscission layer forms between the base of the pedicel and the cluster base. Most abscission occurs within the first 4–6 weeks of growth, culminating in the 'June' drop. 'King' flowers set better than do lateral ones, and those in terminal clusters better than those in lateral clusters. Cultivars differ considerably in set; 'Golden Delicious', 'Paulared' and 'Fuji' set a higher proportion of flowers than do 'McIntosh' and 'Delicious'. For this reason, the former tend to be biennial, the latter annual, bearers. Slow-growing fruits and/or those with few seeds generally drop first, as they are less competitive. When initial set is light, subsequent abscission is less intense, primarily because there is less competition among fruitlets. Cloudy weather limits photosyn-

thesis, thus favouring abscission, and fruit set is generally greater in western regions of the USA where sunlight is abundant than in the humid and cloudy east, and in well-exposed portions of the tree than in the shaded, inner portions (Fig. 7.3). Negative correlations between temperature prior to bloom and fruit set have been reported for several cultivars and locations (Jackson and Hamer, 1980).

Several cultural practices can be used to improve set. Pruning opens the tree to light, thus avoiding excessive shading. This is less of a problem with trees propagated on dwarfing rootstocks than with large trees on seedling rootstocks. The rootstock can also have a further major effect, with set being greater on less vigorous stocks. The addition of major elements, particularly nitrogen, is critical for good fruit set in most orchards. Nitrogen should be applied at least 1 month before flowering so that it will be available at the critical time. Sprays of urea can improve fruit set once sufficient leaf surface is available to absorb this source of nitrogen; however, results have been variable. Although boron sprays improve set in some plum (*Prunus domestica* L.) cultivars, apple is not responsive. Scoring or ringing the bark of the trunk or of large scaffold limbs can reduce the June drop, thereby increasing final set. This is usually done with young trees, in which fruit set can be poor. The treatment is effective only within a few weeks of bloom (see also Chapter 14).

Increasing fruit set when conditions for pollination are poor is more difficult than is reducing crop load when it is excessive. Although GAs can improve fruit set in some species, they do not have this effect in apple. One of the most effective chemicals tested to date for increasing set is aminoethoxyvinylglycine (AVG), an inhibitor of ethylene biosynthesis. Although this compound, marketed as Retain®, is currently used commercially for delaying maturity and reducing preharvest abscission of apple fruits (see Chapter 17), it is not used commercially to improve fruit set.

When fruit set is excessive, the fruit must be thinned to allow more of them to grow to marketable size, as an optimum crop load

results in maximum economic value of the crop as a whole. When set is below the optimum, fruit size is large and therefore the individual fruits are more valuable, but this usually does not compensate for the smaller number of fruits. Early thinning can be accomplished either manually, which is expensive, or by using chemicals that induce abscission of a portion of the flowers or fruits (see below and Chapter 16). Growers often thin with specific chemicals and then hand-thin to remove excess fruits. Early thinning also increases flower initiation for the next year's crop, thereby reducing biennial bearing. Thinning also reduces the danger of limb breakage from excessive weight on limbs, and can improve fruit colour and quality by reducing reciprocal shading among fruits in the same cluster and by increasing the fruit's access to carbohydrates, which are required for both growth and anthocyanin formation.

7.6 Seed and Fruit Growth

About 4–6 weeks after fertilization, the endosperm becomes cellular and soon fills much of the developing ovule (seed) as it grows at the expense of the nucellus (Fig. 7.9). The embryo develops more slowly, but gradually consumes the endosperm and occupies most of the seed at maturity.

During the first 3–4 weeks of growth, both cell division and cell expansion are occurring in the fruitlet. Thereafter, increase in size is almost entirely the result of expansion of cells and intercellular spaces, except in the epidermis, where cell division continues. Although cell expansion contributes much of the volume, cell division is critical in determining final size. Warm temperatures early in the season stimulate fruit growth and increase ultimate size (Warrington *et al.*, 1999), but shorten the period of cell division. The carpellary (ovary) tissue stops growing approximately 6 weeks after bloom, whereas the cortex (fused base) continues to expand (Fig. 7.10). Fruit growth continues as fruit mature; delaying harvest increases fruit size, but over-maturity and excessive preharvest drop may occur.

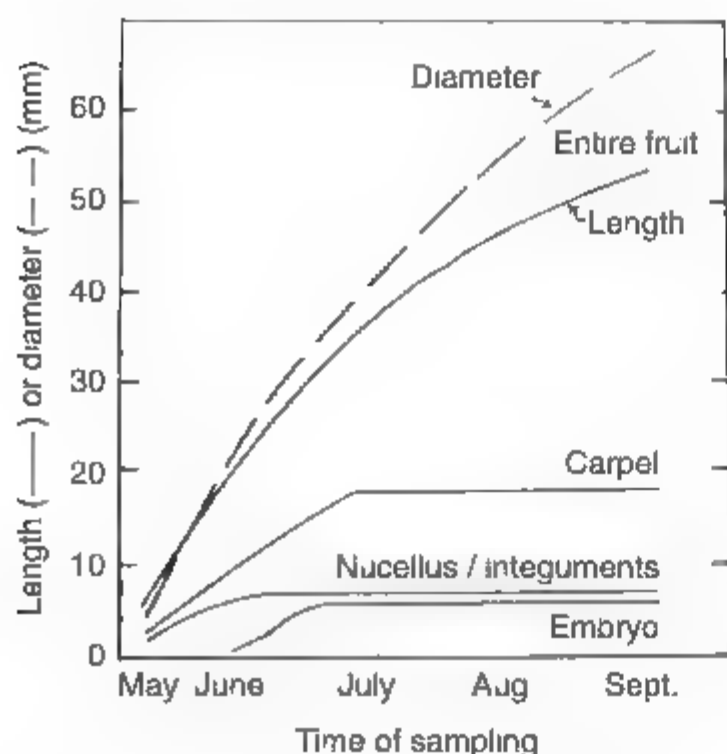


Fig. 7.10. Growth of seed and fruit tissues in a 'McIntosh' apple at Geneva, New York State, from fertilization until maturity (Tukey and Young, 1942)

The major factors determining ultimate size are cultivar and crop load; exposure to light also plays an important part in determining final size (Fig. 7.4; see also Chapter 9). Seed number, rootstock, fruit position in the cluster and on the shoot and spur size also affect the rate of fruit enlargement. Fruit size has been positively correlated with seed number in some cultivars. Size is greater on certain rootstocks than on others, possibly because branch angle is affected, which in turn influences light penetration. In 'Delicious', the 'king' flower produces a noticeably larger fruit than do the lateral flowers, primarily because of larger cells, whereas in 'McIntosh' and 'Empire' the difference is much less pronounced. When only one 'Delicious' fruit is left per cluster, size differences between lateral and terminal fruits are negligible; however, if both a terminal and a lateral fruit are allowed to develop on the same cluster, growth of the latter is retarded, indicating the greater ability of the terminal fruit to attract nutrients (Black and Bukovac, 1996). Size increases with spur leaf area; fruits developing from lateral flowerbuds are smaller than those produced from terminal ones, probably because leaf area is smaller, although the anatomy of the cluster base and flower may be involved as well. For

example, flowers initiated during a heavy crop year may have fewer cells than do those initiated during a light crop year. Large fruits contain more cells than do small ones, and early hand-thinning increases fruit size primarily by increasing cell number. Fruit growth can be limited by water and nutrient supply and by any factors that affect photosynthesis, such as low temperature, cloudy weather and insect injury to the leaves.

Fruit size at harvest can be predicted by measuring fruit diameter during the growing season and projecting the growth curve to harvest. This procedure is useful in evaluating how best to use the fruit (fresh fruit, processing, etc.) and can be helpful in deciding when and how much to thin (Fig. 7.11).

Fruit shape varies with cultivar and stage of development and ranges from oblate (flat) to round to conic. The ratio of length to diameter (L/D ratio) declines as fruits enlarge, resulting in lower ratios for larger fruits (Fig. 7.12). Thus heavy cropping leads to a high L/D ratio. In 'Delicious', cool temperatures during the first few weeks after bloom stimulate growth of the apical portion of the fruit, leading to a high L/D ratio; in warmer areas the fruit are often nearly round (Fig. 7.13). The 'typey' (high L/D ratio) appearance of Washington State 'Delicious' is a selling-point for such fruit and their total weight is greater than non-typey fruit of the same diameter. Rootstock and position on the cluster can also affect the ratio; L/D ratios of 'king' fruit are smaller than those of lateral ones, at least in 'Delicious'. Promalin®, a mixture of benzyladenine (BA) and GA₄₊₇, is used commercially to stimulate growth of the apical portion of the fruit to produce a 'typey' appearance.

7.7 Fruit Maturation

Cultivars differ widely in time of ripening; some (e.g. 'Lodi') ripen within 60 days after full bloom (DAFB) while others require 180 days or more to mature (e.g. 'Granny Smith'). Rootstock also can affect time to maturity, but has much less effect than does cultivar. Heavy cropping delays maturation. Climatic factors also affect maturation, tem-

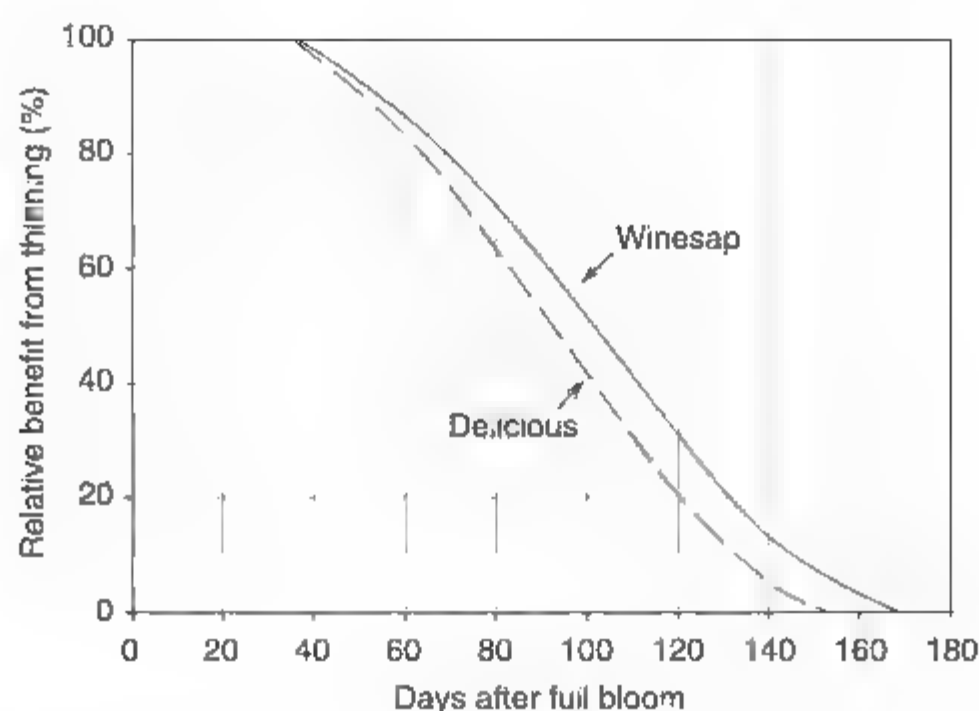


Fig. 7.11. Calculated percentage benefit, in terms of fruit size, of thinning apples at various times after full bloom (Batjer *et al.*, 1957).

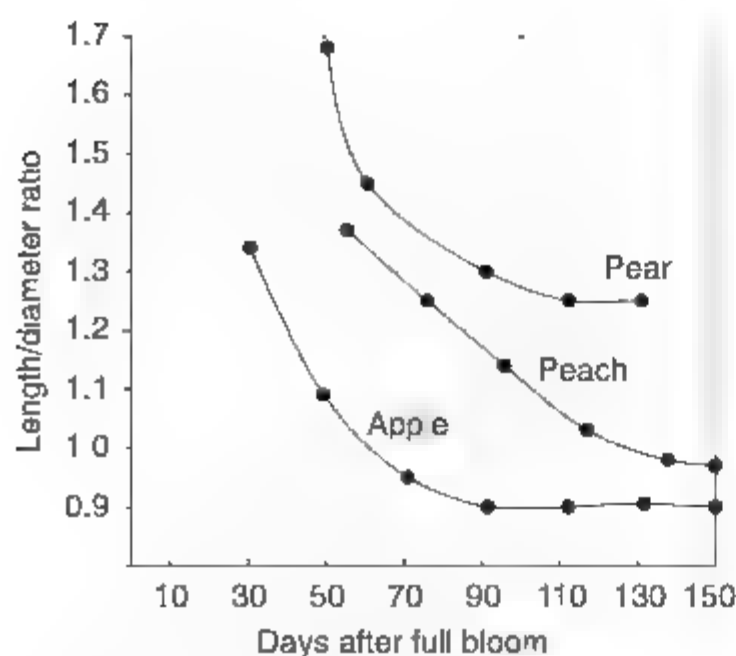


Fig. 7.12. Change in L/D ratio of apple, peach and pear fruits during fruit development (Westwood, 1993)

perature and solar radiation being the most important. Low spring and summer temperatures delay maturation; the time from full bloom to harvest of a given cultivar is longer in Norway than in Italy because of the cooler climate. Exposure to sunlight not only increases red coloration; it also increases fruit sugar content because of its effects in stimulating photosynthesis in adjacent leaves. Fruits in heavily shaded parts of the tree are not only smaller and greener but less mature as well.

Several methods are available to determine and/or predict optimum time of harvest. These include methods based on temperatures early in the season, the ethylene content of/production by the fruit and other properties, such as firmness and concentration of soluble solids.

Chemicals can be used to either hasten or delay maturation (see also Chapter 17). Apple is a climacteric fruit – a burst of carbon dioxide and ethylene production, termed the 'climacteric', occurs in the fruits as they ripen – and ethylene acts as a ripening hormone. Sprays of ethephon, which releases ethylene within the treated tissues, can be used to hasten maturity in order to obtain higher prices. Ethephon is generally used only with the earliest cultivars. Because it stimulates ripening, the fruits cannot be stored for long periods, but such early cultivars generally do not have a long storage life, even without ethephon treatment. Furthermore, the prices for them fall quickly as better, later-maturing, cultivars become available.

Chemicals that delay maturation – and retard preharvest fruit abscission – include Alar®, which, as noted above, is no longer available for commercial use, and Retain® (= AVG, mentioned above). To be effective, these chemicals must be applied approximately 1 month before harvest. Delaying

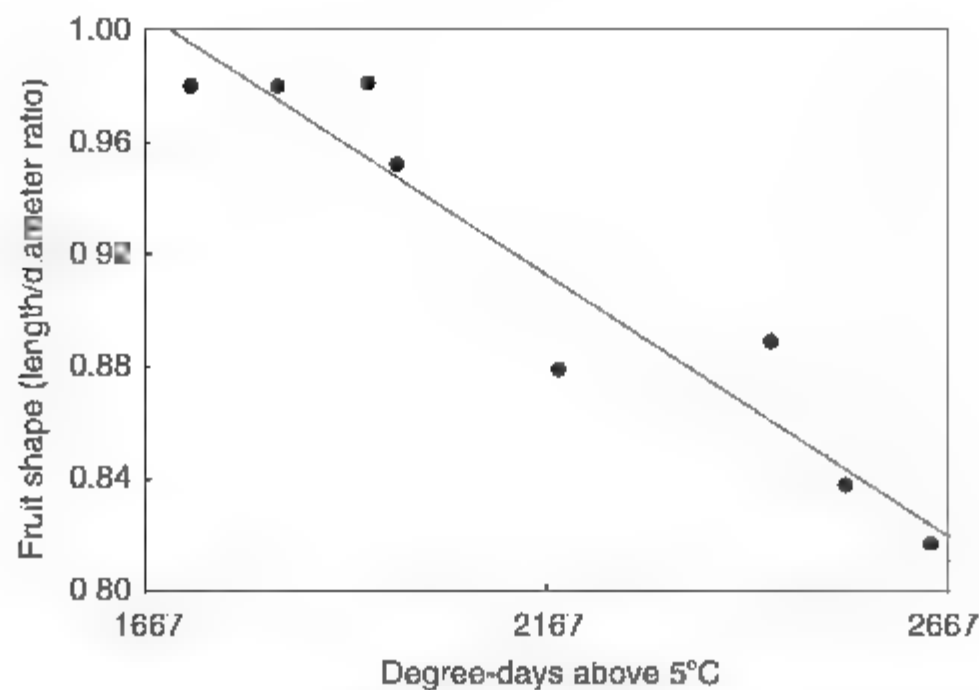


Fig. 7.13. Effect of temperature during the growing season on final length/diameter ratio of 'Delicious' apple fruit (Westwood, 1993).

maturity prolongs both the harvest season and the fruit's storage life and allows more time on the tree for the fruit to develop both size and red colour. Certain auxins used to delay abscission, such as naphthaleneacetic acid (NAA) and 2,4,5-trichlorophenoxypropionic acid (2,4,5-TP), both delay abscission and hasten maturity. However, the former effect is short-lived; if the fruits are not harvested within 10–14 days of treatment, abscission can be stimulated rather than inhibited.

7.8 Summary

In crops whose marketable organs are fruits and/or seeds, such as apple, flowering, fruit set and development are critical for economic return. Some apple cultivars tend to set too many fruits resulting in small size

and inhibition of subsequent flowering – hence biennial bearing – unless the crop is reduced by early thinning. Pollination and fertilization are essential for fruit set. Although some cultivars are self-fruitful, cross-pollination is required in most and is usually advantageous even in self-fruitful ones. Bees are the primary pollinators, and climatic conditions during bloom are critical for fruit set. When fruit set is excessive, the fruits must be thinned mechanically or chemically to encourage fruit growth and flower-bud formation. Cultivars differ in the time required for maturation, some ripening in midsummer and some in late autumn. Preharvest drop can be a problem in some years and with some cultivars. Chemicals can be used either to hasten ripening or to delay it, allowing growers to harvest earlier or later than would otherwise be the case.

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8 Water Relations of Apples

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8.1 Basics of Water Relations of Apple Trees

Water relations are very important to the function of the apple tree, as water is the greatest component of the tree by mass and almost all critical processes can be limited by inappropriate water status. The essential role of water, however, does not mean that the water is always limiting or is regulating variations in productivity. This chapter will address some of the times and conditions (natural and culturally imposed) under which the water relations may be controlling tree behaviour. Specific reviews are available on water relations and irrigation of fruit-trees (Elfving, 1982; Jones *et al.*, 1985; Bravdo and Proebsting, 1993) and on apple (Landsberg and Jones, 1981; Lakso, 1994; Behboudian and Mills, 1997), so this chapter will focus on an interpretative review of more recent information.

8.2 Concepts of Water Relations

Water relations of plants are typically described in terms of the thermodynamics of water activity and are expressed in terms of megapascals (1 MPa = 10 bars as used in older papers). The components of water relations and measurement methods will be reviewed briefly to provide a basis for later discussions. The reader is referred to excellent books by Nobel (1991) and Jones (1992) for more detailed discussions on water relations, but a brief review will follow

8.2.1 Water potential components

The total water potential is made up of several components of varying sign as to

whether they increase or decrease water activity:

$$\begin{array}{ccccccc} \text{Total} & = & \text{Osmotic} & + & \text{Turgor} & + & \text{Matric} & + \\ (-) & & (-) & & (+) & & (-) & \\ & & & & & & \text{Gravitational} & \\ & & & & & & (-) & \end{array}$$

Normally, gravitational potential changes only by 0.01 MPa m⁻¹ above the ground, so it can be ignored except in very tall trees. Similarly, the matric potential is the reduction in potential due to interactions of water with surfaces, so it is important in soils. However, it is usually included in the osmotic-potential measurement for plant cells.

8.2.1.1 Total water potential

Total water potentials (Ψ_w) are controlled by the balance of osmotic and turgor potentials. Within the tree, total water potentials describe the gradients for water movement, with water moving from high (less negative) to low water potentials. So the primary importance of total water potentials is to determine the direction of water movement and strength of gradient for that movement.

8.2.1.2 Osmotic potential

Osmotic potential or solute potential (Ψ_s) is the lowering of water activity by the interaction of water with solutes in the cell. It is a 'colligative' property, which means that it depends on the concentration of the solutes, not the size of the molecules. So a mole of potassium ions has the same effect on osmotic potentials as a mole of glucose. Adjustments in the osmotic potential of a cell or tissue modify the relationship between total and turgor potentials. At a constant

total water potential, a more negative osmotic potential due to accumulation of solutes will increase turgor. For example, the variation in turgor and opening of stomata is controlled primarily by fluxes of potassium ions into and out of the guard cells. Conversely, as water potential becomes more negative with drought stress, leaves of apple can lower the Ψ_s (i.e. it becomes more negative) by accumulating sugars and other solutes to maintain turgor and leaf function, as will be discussed later (Goode and Higgs, 1973; Lakso *et al.*, 1984). Apple fruits also accumulate many solutes during development that affect the fruit Ψ_s and fruit water relations. Additionally, the hydrolysis of starch to sugars as the fruit matures lowers the Ψ_s (i.e. it becomes more negative) without requiring imported carbohydrates.

8.2.1.3 Turgor potential

Turgor or pressure potential (Ψ_p) refers to the changes in water activity due to the positive pressures that develop as water is drawn into cells by the osmotic reduction of water activity. Turgor pressure is critical as the energy source for expansive growth of cells and for tissue turgidity of all parts of the tree. Many plant processes seem to sense turgor, although the mechanisms of sensing are not well known. Ψ_p normally changes with total water potential unless there is a compensatory change in osmotic potential that may help maintain Ψ_p at a more constant level.

8.2.1.4 Relative water content

Relative water content refers to the amount of water that a cell or tissue holds as a percentage of what it could hold when fully hydrated (analogous to relative humidity). It is related to the total and turgor potentials, but not directly

8.2.2 Plant hydraulic resistance

Plant hydraulic resistance (R) refers to the resistance within the vascular system to water movement along the gradients of total water potential. The main significance of

plant resistance is that it affects the relationship between the water-potential gradient and the transpiration flux of water (E). This relationship is expressed as an analogy to the electrical Ohm's law for the relationships among a potential gradient (voltage), a resistance and a flux (current):

$$E = d\Psi_w / R$$

Compared with many plants, such as annuals, apple trees have a high hydraulic resistance (Fig. 8.1). This means that a relatively large gradient of Ψ_w is needed to move enough water through the tree to maintain any given transpiration rate. The intercept at $E = 0$ is controlled by the soil water potential, the minimum value at mid-day is determined by E , while the slope of the relationship is the tree resistance, which is mostly in the apple root system (Landsberg and Jones, 1981).

Consequently, for similar transpiration rates, apple trees, and many other trees, will show a much greater diurnal decrease in leaf water potential than do annuals. This is seen in the typical strong diurnal decline of leaf water potential of apple leaves on a sunny day (Fig. 8.2). Because the predawn water potential is determined by the soil water potential if the E rate is near zero, predawn leaf water potentials are used as estimates of

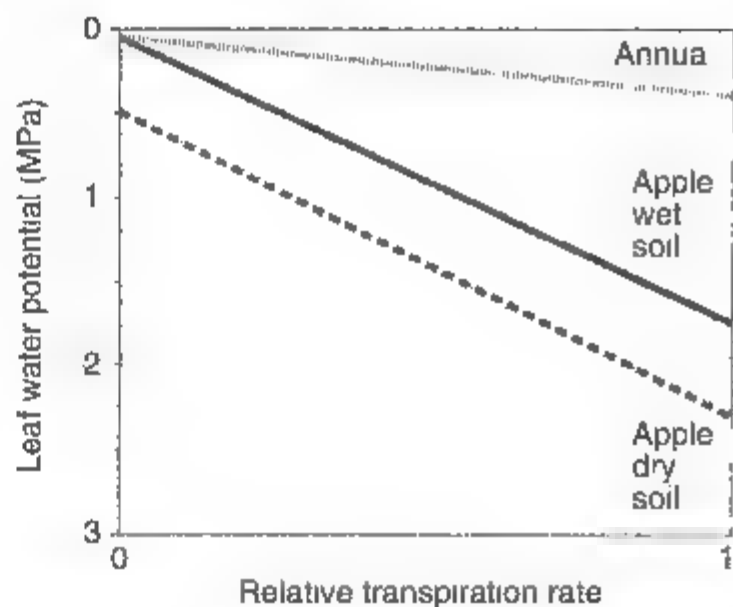


Fig. 8.1. General relationship of leaf total water potential of the top of the tree to the transpiration rate. The steeper the slope, the greater the hydraulic resistance. Soil water potential affects the intercept where $E = 0$

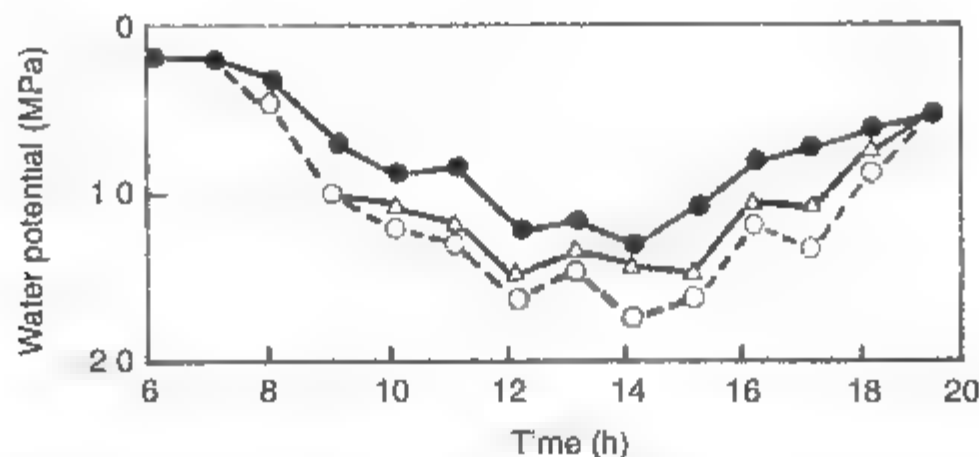


Fig. 8.2. Diurnal patterns of apple leaf total water potentials on trees irrigated to the soil (triangles) or by misting the canopy (solid circles) compared with unirrigated controls (open circles) (adapted from Brough *et al.*, 1986, with permission).

effective soil water potential around the roots. This can be useful, as representative placement of soil moisture measuring devices is difficult since apple root systems have very low density and are erratic in distribution (Atkinson, 1980; Hughes and Gandar, 1993; de Silva *et al.*, 1999).

Since E varies with the evaporative conditions, the leaf Ψ_w also depends strongly on evaporative conditions of the atmosphere, as shown by the effectiveness of aerial misting on reducing the diurnal pattern of leaf water potential (Goode *et al.*, 1979; Brough *et al.*, 1986; Fig. 8.2). This is not the case for a plant that has low hydraulic resistance, such as the sunflower (Fig. 8.1). In apple, however, atmospheric conditions are much more important to the control of Ψ_w (see Jones *et al.*, 1985, for a more detailed discussion). This means that:

- Soil moisture measurements cannot be used alone to estimate midday water potentials, which depend more on evaporative demands.
- Water potentials will be highly variable if the conditions are variable
- Therefore, the uniformity of environmental conditions is critical for measurements when comparing the water potential effects of treatments (i.e. measurements must be compared under similar conditions).
- Cool, humid conditions will ameliorate a soil drought while hot dry conditions will aggravate the drought effects (Sritharan and Lenz, 1989).

8.2.2.1 Water-use efficiency (WUE)

The WUE of a plant is typically the carbon gained per unit of water lost. It may be expressed in instantaneous net photosynthesis rate per transpiration rate, or it may be a long-term integral of dry matter per volume of water loss. In apple trees in the field, we have found good WUE, since the stomata maintain an optimal conductance that is tightly coupled to the photosynthesis rate (Lakso, 1994). The net effect is that the stomatal conductance adjusts so that, for example, reductions in the photosynthesis rate due to lack of crop or some form of girdling are matched by reduction in conductance.

8.3 Measurement of Apple-tree Water Status

8.3.1 Water-potential measurements

The most common method of measuring tree water status has been to estimate exposed-leaf total water potential (Ψ_w) with a Scholander pressure chamber (also known as the pressure bomb). Although many leaf processes, such as stomatal opening and photosynthesis, are correlated with Ψ_w , the limitations of using Ψ_w alone include: (i) significant osmotic adjustment in the apple, which can change critical levels of Ψ_w (Lakso *et al.*, 1984); (ii) variability due to individual leaf exposure and transpiration rates so that exposed-leaf Ψ_w may not represent shaded leaves, fruit or shoot tips, which do not transpire as much (Higgs and

Jones, 1990); and (iii) stomatal closure may reduce transpiration enough to stabilize exposed-leaf Ψ_w so that Ψ_w is not related to internal water status (Jones *et al.*, 1983).

Another common method, predawn leaf Ψ_w , indicates effective potential at the soil/root interface under near-zero transpiration if the soil moisture is homogeneous. With deep root systems, especially with drip irrigation, the predawn reading represents the wettest part of the soil, not the average (Jones, 1990; Ameglio *et al.*, 1999). Consequently, the predawn value may not be a good measure of midday stress under high transpiration flow if only a small portion of the soil is wet. Consequently, a more integrative method is the estimation of midday stem potential (Ψ_{stem}) by enclosing a leaf in a plastic bag with foil to shade the bag (Powell, 1974; Olien and Lakso, 1986; Jones, 1990; McCutchan and Shackel, 1992). This stops transpiration and allows the leaf to equilibrate with the water potential in the stem at that point. The Ψ_{stem} is a more integrative and stable measurement since it is influenced by all the leaves and organs of the branch. It is also a better estimate of the potential experienced by fruits, shoot tips and other organs that do not transpire rapidly. The Ψ_{stem} value is probably the best single measure of plant water status and is recommended (Naor, 2000). A promising approach is to integrate midday stem potentials over a season into a 'crop water-deficit index', which was found to be well correlated with apple fruit growth and weight at harvest (Ebel *et al.*, 2001).

8.3.2 Trunk- and fruit-diameter monitoring

The shrinking and swelling of apple-tree trunks and fruit in relation to soil moisture deficits and evaporative demand have been recognized for many years (Furr and Magness, 1930; Verner, 1937; Harley and Masure, 1938; Taerum, 1964). The advantages are: (i) the measurement can be monitored continuously so is less dependent on the environment at any one time; and (ii) the trunk and fruit better integrate the whole-tree water status than any single leaves. Almost 40 years ago Tukey (1963) developed an early electronic device for

monitoring these changes and proposed this as a method for irrigation timing. Since then several studies have evaluated this method (Powell, 1976a; Assaf *et al.*, 1982; Higgs and Jones, 1984; Iancu, 1985), although apparent contradictions in behaviour need to be reconciled (Huguet *et al.*, 1992; Bonany *et al.*, 2000) before this method can be used in the field.

8.3.3 Stable isotope discrimination

This method is based on the discrimination against stable isotopes of different molecular weight (^{13}C , ^{16}O and ^2H) during diffusion and exchange processes in the soil and in the plant (see Ehleringer *et al.*, 1993). Discrimination of ^{12}C and the heavier $^{13}\text{CO}_2$ during gas exchange is an integrator of variations in water-use efficiency, a major advantage over the instantaneous methods generally used. In apple, Behboudian's group (Behboudian *et al.*, 1994; Mills *et al.*, 1998) found that high root temperatures reduced transpiration and discriminated against ^{13}C and that deficit irrigation had similar effects, although the differences were quite small. The need for an integrator of stress is even greater with apples, since the water relations of apple trees are so dependent on the dynamic evaporative conditions; instantaneous measurements during stable midday conditions may not represent a large proportion of the long-term conditions. However, it is possible that the carbon isotope method may not be as promising as hoped because in the field apple leaf stomata are well coupled to photosynthesis and mature leaves can osmotically adjust (Lakso, 1994).

8.4 Root-system Characteristics and Influences on Water Relations

Two of the key characteristics of the apple tree root system of relevance to water relations are: (i) an extremely low root-length density in soil; and (ii) a very non-uniform root distribution. Several studies of apple root systems have shown that apple root-length densities are very low compared with grasses (Landsberg and Jones, 1981; Hughes and

Gandar, 1993; de Silva *et al.*, 1999; Green and Clothier, 1999). There are several implications of such low root density and erratic rooting.

8.4.1 Availability of soil water and nutrients

One important implication is that the effective soil volume that is explored for water and nutrients is reduced, especially in relation to non-mobile nutrients. There may be relatively large portions of the potential soil volume that are not explored by fine apple roots. This can be seen in the results of Atkinson and Wilson (1980), who found a relatively high percentage of soil cores under mature apple trees at different distances and depths to have no or few apple roots in them.

The sparse rooting also means that the average distance that is required for water and nutrients to travel through the soil is much greater for apple root systems than for dense uniform root systems, such as grass. In competitive interactions of apple roots with weeds or cover crops, the apple roots are generally very poor competitors. Normally, apple roots will not be able to establish in zones of weed or cover-crop root growth and generally will require at least a minimum amount of surface soil with no competing plants even with irrigation (Merwin and Ray, 1997). This may further reduce the available soil volume for water and nutrient uptake. However, it may also provide a management tool to purposely restrict tree growth or, conversely, to improve growth by removing the competition of plants between the rows. In arid climates in which the tree depends on irrigation for most of the season, root distributions may concentrate in the wetted zone, especially if nutrients are supplied by fertilization (Huguet, 1976; Levin *et al.*, 1979, 1980; Bravdo *et al.*, 1992; Neilsen *et al.*, 2000).

8.4.2 Implications for plant resistance and water status

As discussed above, the apple root system has a quite high hydraulic resistance. An additional component of this can be the resistance of the soil in the rhizosphere (the inter-

face of the root and soil). Soil resistance for water movement increases markedly as the soil dries and as the distance of travel to the root increases. Based on estimates of crop water use in arid climates, apple orchards in mid-season transpire almost as much as grass fields (Ley, 1994b; Allen *et al.*, 1998; Hanson *et al.*, 1999), even though the root density of the grass may be 1000 times higher than that of the apple (Landsberg and Jones, 1981). Atkinson and Wilson (1980) proposed that the very low root-length density, combined with the high water uptake required of each root, will lead to localized drying in the rhizosphere during times of high transpiration at midday. This would occur if the soil could not supply water to the rhizosphere as fast as it was taken up by the roots. Landsberg and Jones (1981) calculated that the soil plant resistance would increase much more rapidly in drying soil for plants with low root densities such as apples. Direct evidence is lacking, but Bonany and Camps (1998) found that tree growth and fruit size increased with irrigation rates up to 150% of crop evapotranspiration (ET). This has also been seen in almonds, grapes and citrus (Hutmacher *et al.*, 1994; Williams, 1996; Parsons *et al.*, 2001). This question deserves more attention to determine its importance and if there are ways to manage the effect for benefit.

8.4.3 Root growth and water uptake

In most studies of water and nutrient uptake, it is concluded that young, white roots are the most efficient, especially for phosphorus uptake, although older roots are still quite active (Atkinson and Wilson, 1980). This implies that flushes of new root growth should stimulate better water and nutrient uptake. Surprisingly, there is little direct evidence in apple for this conclusion. In part this is due to little knowledge of when roots in fact are growing during the season. The many detailed studies of apple root growth at the East Malling Research Station rhizotron over several decades (see Atkinson, 1980, 1983) provided much information, but were limited to one site. Recent studies in New York State found that, over several seasons, new root

production generally did not occur until about 1 month after bloom and the great majority of growth was completed in 60–80 days (Psarras *et al.*, 2000; A. Lakso and K.-T. Li, unpublished data). However, in a warm dry year with heavy crop loads, new root production peaked at bloom and again postharvest, with little growth in midsummer. Clearly, the seasonal pattern of root production is rather plastic. These patterns of growth have not been correlated with water status or nutrient uptake, however. In general, Atkinson (1980) concluded that new fine roots are not required for adequate water and nutrient uptake by apple trees. There needs to be much more research integrating root and top growth with water relations and nutrient uptake.

8.4.4 Mycorrhizae and water uptake

Apple roots have vesicular arbuscular mycorrhizal (VAM) associations, which probably play an important role in extending the surface area for absorption of immobile nutrients, such as phosphorus (Trappe *et al.*, 1973; Plenchette *et al.*, 1982; Gnekow and Marschner, 1989). Good growth of apples appears to depend on the VAM association, but apples appear normally to have VAM in the field. There has been a report that the water uptake and water status of apple seedlings in sterile medium were improved by inoculation with VAM (Runjin, 1989). How important the mycorrhizae are to water uptake and status of mature apple trees in the field is not clear. Koide (1993) concludes that non-nutritional mycorrhizal effects on water relations are minimal; however, Auge (2001) concludes that there may be direct effects in many plants as well as nutritional and plant size-related effects. Considering the very low root-length density of apples and the likelihood of localized drying in the root-soil interface, it seems likely that mycorrhizae could improve water relations by improving the root-soil contact. This is another area that needs further research to clarify. If we understand more we may be able to vary soil and management practices as they have been shown to affect mycorrhizae in crops (Barea *et al.*, 1993; Dorgo *et al.*, 1997).

8.5 Water Use by Apple Orchards

The most direct method to measure water use is by lysimeter, which can monitor either weight loss (weighing lysimeter) or the amount of water required to return the soil to field capacity (drainage lysimeter). Although there have been several lysimeter studies on apple, quoting actual totals for water use is not helpful, as the rates of water use varied depending on the climate where the work was done and the unique combinations of tree characters and environment, which are typically not reported. These factors will be reviewed below.

A useful expression is the water-use rate per unit leaf area in midsummer. In the mild sub-humid climates of The Netherlands (Kodde and Kipp, 1990), Germany (Chen and Lenz, 1997; and calculated from data in Braun *et al.*, 2000), New Zealand (Green and Clothier, 1988; Green *et al.*, 1995; Mpelasoka *et al.*, 2000b) and New York State (A. Lakso, 1997 and 2001, unpublished data), it has been found that water-use rates on sunny days are approximately 1–1.7 l m⁻² of leaf area. In the south of France, Angelocci and Valancogne (1993) found in July that mid-season rates were correlated to leaf area but could exceed 2.5 l m⁻² leaf area day⁻¹ in arid climates.

8.6 Factors that Affect Water Use in Apple Orchards

Water use by apple orchards varies with tree characteristics and climate. The principles regulating water use by crops have been studied over many years and they provide the basis for understanding the variations observed (Allen *et al.*, 1998). In short, ET by crops is ultimately driven by energy from solar radiation, but it is modified by temperature, vapour-pressure gradient (VPG), boundary layers of still air and conductance of the crop.

8.6.1 Energy, radiation and humidity

Transpiration of plants is driven by energy from solar radiation, which heats the air and exposed surfaces, such as soil, water and

leaves. Although we generally consider VPG of the air, or from leaf to air, as a driving variable, transpiration is also based on the energy from solar radiation. This energy provides the potential for ET and may be received directly by the orchard or may be imported into the orchard by the movement of outside air of varying temperature and VPG. Although the energy determines the potential for water use by trees, several other important factors affect the actual water use.

8.6.2 Leaf area

The amount of leaf area on a tree is important to its water use since the leaves provide the most active transpiring surfaces and they also intercept the radiation that drives transpiration. As the leaves intercept radiation, the energy warms the leaves and provides the energy for the evaporation of water within the stomatal cavities of the leaves. Consequently, water-use rates vary over the season with the development and loss of the leaf canopy and the related radiation interception. A similar effect occurs over the development of the life of the orchard as the canopies fill their space and intercept more radiation. A good correlation of apple tree water use to leaf area has been found (Wibbe and Lenz, 1989; Angelocci and Valancogne, 1993), although there was probably also a correlation of leaf area to radiation interception.

A recent study in our laboratory has shown that reductions in leaf area and radiation interception due to summer pruning of mature apple trees also reduces water-use rates (Fig. 8.3). The reduction in transpiration rates was less than the reduction in leaf area, since the pruning increased the proportion of leaf area that was exposed and reduced the light interception less than the leaf area. The lower transpiration of the pruned trees consequently translated into less negative stem potentials. In drought years such summer pruning may provide a method to improve the water status of unirrigated trees without affecting soil moisture. Severe pruning of peach and pear trees has been demonstrated to reduce extreme drought effects (Proebsting and Middleton, 1980).

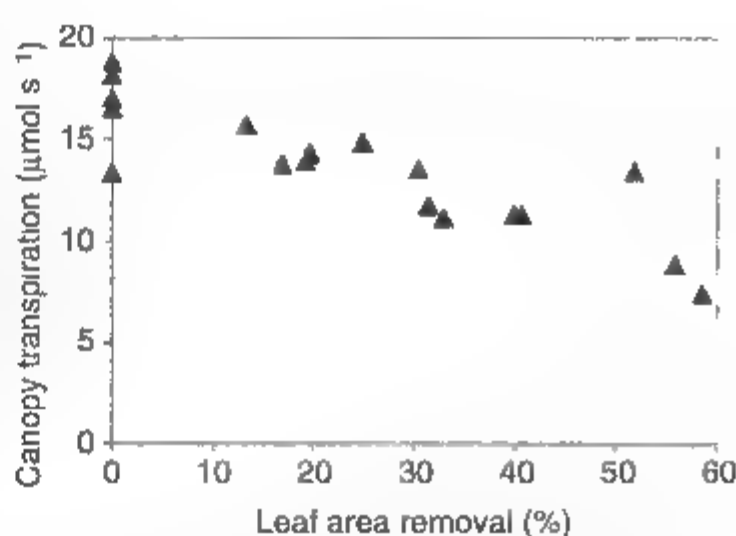


Fig. 8.3. Effects of reducing leaf area with varying severity of summer pruning on the canopy transpiration rate of apple trees as measured with whole-canopy chambers under sunny conditions (K.-T. Li and A. Lakso, 2001, unpublished data).

Beyond the role of leaves in intercepting radiation, interior shaded leaves of trees still transpire, although at lower rates than exposed leaves. This suggests that trees with many shaded leaves will have lower WUE, since Marangoni *et al.* (1992) found that the shaded leaves with less than 10% of full light had only 10% of maximum photosynthesis but 50% of maximum transpiration. The transpiration rate may not be valid, due to the artificial conditions of the leaf chamber, but this author has found that the leaf conductances of shaded leaves may be up to 60% of that for exposed leaves. It has been shown in grapevines with whole-canopy chambers that removing about 25% of the total leaf area, but only from the inside of the canopy, had little effect on canopy photosynthesis, but reduced transpiration by about 10% (S. Poni, personal communication).

8.6.3 Crop structure and boundary layers

The tall structure of apple trees, especially in rows, makes a very aerodynamically rough structure. Consequently, air mixes in the canopies very well, so that the leaves are well coupled to the environment. Thick, still boundary layers of air, which can trap transpired humidity over low crops like grasses or cover crops, do not develop over the canopies of apple trees (Jarvis, 1985). Because of the excel-

lent mixing of bulk air with the crop, the leaves are exposed to the bulk-air humidity. This means that radiation and bulk-air VPG are both important environmental regulators of water use in apples, along with stomatal conductance. This will be discussed further later.

8.6.4 Factors affecting stomatal opening

Since stomatal opening has an important role in regulating apple tree transpiration, factors that affect stomatal conductance are of importance. In apple trees in the field, it appears that the stomata are well coupled to photosynthesis, usually not opening more than needed to maintain a constant internal CO_2 (Lakso, 1994). This means that factors affecting photosynthesis will also affect transpiration. Crop load has been shown to positively affect gas exchange and water-use rates in several ways. Stomatal conductance and photosynthesis of leaves are reduced as very low or zero crop loads are reached (Palmer *et al.*, 1997); thus non-cropping trees use less water per unit of leaf area (Hansen, 1971; Lenz, 1986; Navara, 1987; Wibbe and Lenz, 1989; Buwalda and Lenz, 1992; Masarovicova and Navara, 1994; Blanke, 1997; Chen and Lenz, 1997). If, however, the cropping reduces leaf area more than it stimulates the transpiration per unit leaf area, the total tree water use may decline (Fig 8.4).

8.6.5 Canopy form, spacing and light interception

The canopy form and spacing of apple trees can have a significant effect on water use by orchards, with wider or larger tree forms using more water than thinner or more vertical forms. This effect is probably related to the varying effects of training systems on light interception and secondarily on leaf area. Broader canopies, such as Y- or V-shaped trees, or orchards that are spaced more closely will intercept more light than narrower, more widely spaced forms (Jackson, 1980; Jones *et al.*, 1985; Palmer, 1989; Robinson and Lakso, 1991; Lakso, 1994) and will use more water (Chen and Lenz, 1997).

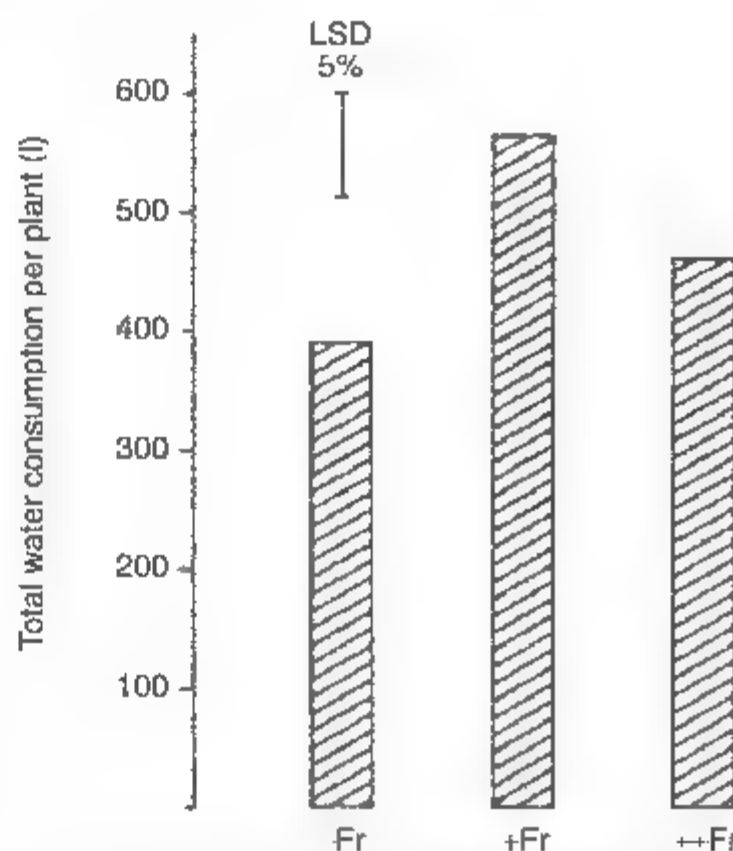


Fig. 8.4. Total water consumption of apple trees over 3 years if the trees never carried a crop (–Fr), carried a crop in the third year (+Fr) or carried crops in the second and third years (++Fr). Leaf areas per tree were 4.9, 3.4 and 2.5 m^2 , respectively. (Reproduced from Lenz, 1986, with permission.)

Increasing planting density has also been shown to increase water use (Atkinson, 1981).

8.6.6 Interactions with drought

As drought develops in apple trees, there are several responses that affect orchard water use (Landsberg and Jones, 1981; Jones *et al.*, 1985; Lakso, 1994). A reduction in vegetative growth due to early-season stress will reduce leaf area and possibly canopy light interception. Crop load may be reduced by early stress (Powell, 1974), leading to lighter crop loads and the related effects. These responses can cause adjustments in water requirements. Of course, stomatal closure is important, as well as leaf abscission in extreme cases.

8.7 Water Deficits and Apple-tree Growth, Cropping and Physiology

If the water-use demands of a tree cannot be met, stress will develop. The effects of water

stress on apple-tree growth and function have been reviewed in depth previously by Landsberg and Jones (1981), with additional reviews more recently (Jones *et al.*, 1985; Lakso, 1994; Behboudian and Mills, 1997). This review will summarize the main conclusions from these reviews and integrate more recent information.

8.7.1 Timing of stress

A general observation is that processes that involve growth by expansion and especially those involved in growth by cell division are more sensitive to water stress than processes such as cell expansion, storage and gas exchange (Hsiao, 1973). Consequently, water stress that develops in the spring and early summer can have dramatic effects on vegetative growth, fruit growth and fruit set, because early-season shoot growth and early development of fruits are primarily by cell-division processes (Powell, 1974; Ferree and Schmid, 1990). Water stress that develops more typically in midsummer will have less effect on vegetative growth and less effect on fruit yield, as canopy development and fruit set are complete or nearly so by midsummer. Postharvest water stress has not been examined extensively, since there is the general feeling that it is too late to significantly affect physiological and growth processes. This may not be true in long-season climates, since there may be several months of good weather and active physiological processes before leaf fall. Late-season processes, such as flower-bud development, root growth and nutrient uptake, reserve storage and winter acclimatization, would be expected to be affected by stress, although water-stress effects late in the season in warm climates need more study (Kuroda *et al.*, 1985).

8.7.2 Vegetative growth

Since adequate water is needed for the turgor to drive expansive growth of apple leaves (Davies and Lakso, 1979b), shoot growth is sensitive to water deficits. Detailed measurements of shoot growth rate in relation to plant

water potentials indicate that shoot expansion is almost linearly reduced by declining mid-day stem water potentials (Fig. 8.5). Although mature leaves can osmotically adjust to maintain turgor, apple shoot tips do not (Lakso *et al.*, 1984). Therefore, shoot-tip turgor and growth will decline directly with declining water potentials. Fruits and roots have been shown to adjust osmotically for turgor maintenance (Beruter, 1989; Failla *et al.*, 1992; Wang *et al.*, 1995; Mills *et al.*, 1997). Again, the evaporative demands on the canopy will accentuate or ameliorate the effects of changes in soil water potentials by affecting the water potentials during the afternoon when it appears that apple shoots grow (Powell, 1976a). Very similar responses have recently been documented for peaches, which also grow primarily in the late afternoon and evening (Berman and DeJong, 1997a,b).

Root growth in a rhizotron has been shown to be reduced in response to drying soil (Rogers, 1939), although compensatory growth may occur in the wet-soil zones. Over several months of rain-shielding, Jones *et al.* (1983) found that the shielded trees produced more root length than either the rain-fed controls or shielded trees with added irrigation. Goode *et al.* (1978), however, found more surface roots under irrigated trees but no effects

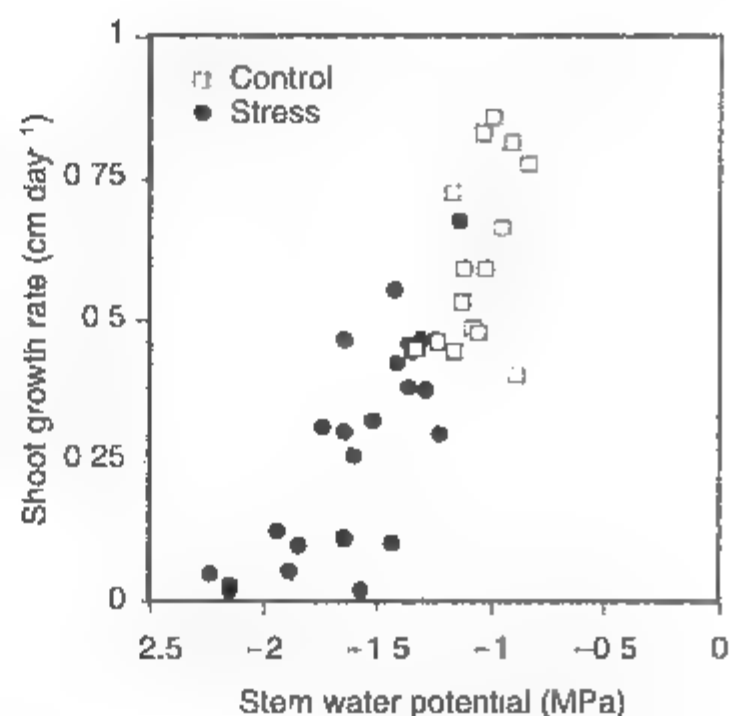


Fig. 8.5. Relationship of extension-shoot growth rate to variations in midday stem water in apple trees as affected by drought stress (M. Al-Hazmi and A. Lakso, unpublished data).

deeper in the soil. Although individual roots may slow growth in relation to drying soil, the behaviour of the whole root system is probably much more complex, as it responds to variable soil moistures in the field. Several studies have shown that in arid climates over time apple roots tend to concentrate under drip emitters (Huguët, 1976; Levin *et al.*, 1979, 1980; Crew and Funk, 1980; Bravdo *et al.*, 1992; Neilsen *et al.*, 2000).

It should be noted that, due to the strong relationship of water potential to transpiration (Fig. 8.1), the severity of any soil-moisture stress on leaf behaviour or growth will be accentuated by higher evaporative demands and, conversely, ameliorated by cooler, lower-demand conditions. Consequently, as the soil moisture declines, stomatal opening and water loss will be maintained longer if the weather is cool and humid than if it is hot and dry. A related factor is that slower stress development allows apple leaves to osmotically adjust markedly, which allows stomata to stay open longer than expected (Goode and Higgs, 1973; Lakso, 1979; Lakso *et al.*, 1984; Jones *et al.*, 1985).

8.7.3 Fruit growth, quality and postharvest effects

The effects of water stress on other fruit-quality and postharvest characteristics are complex and variable, since water relations affects so many plant processes. In his review Sharples (1973) stated:

It is seldom possible to separate the effects on the fruit which are due to water supplies alone. For example, variable levels of irrigation influence the overall nutrition and growth of the tree, and any observed effects on fruit storage quality may be due as much to these general influences on the tree as to any specific influence of the water supply to the fruits.

A common effect is the increase in vegetative growth with irrigation, leading to denser canopies and more shaded fruits, which show effects of both water and shade. Also, early stress that leads to reductions in fruit set causes many crop load-induced differences in fruit quality, making differentiation of causes difficult.

Water stress reduces several aspects of fruit growth and development. Fruit set in the first weeks after bloom appears to depend on maintenance of an adequate rate of fruit growth. Therefore, reductions in fruit growth during the early cell-division period can reduce both fruit set and the potential for good fruit size at harvest (Powell, 1974), although often these early-season processes are completed before severe stresses develop. Reductions in fruit growth are the most common fruit responses to water stress in apples (Lord *et al.*, 1963; Guelfat-Reich *et al.*, 1974; Assaf *et al.*, 1975, 1982; Goode *et al.*, 1978; Lötter *et al.*, 1985; Ebel *et al.*, 1993; Kilili *et al.*, 1996b; Mills *et al.*, 1996). The effects of water stress on fruit development appear to be more severe if the stress occurs during the cell-division period compared with during the cell-expansion period. Reductions in growth during cell division are manifested over the remainder of the season, even if water is abundant later (Fig. 8.6). The reduction in fruit size caused by water stress may cause firmness to increase. In some cases, this increase in firmness has been found to be independent of fruit size (Mpelasoka *et al.*, 2000a), while, in several cases, the increase was not significant when comparable fruit sizes were compared (Lord *et al.*, 1963; Ebel *et al.*, 1993).

There are many apparent contradictions in the many reports of water stress on fruit-quality effects, but several general trends occur. Besides the strong effect on fruit size, increases in fruit dry matter or per cent soluble solids have been quite consistent (Assaf *et al.*, 1975; Ebel *et al.*, 1993; Kilili *et al.*, 1996a; Mpelasoka *et al.*, 2000a). Mills *et al.* (1994) found the effect of water stress on dry matter and per cent soluble solids to decrease with later harvests, suggesting late-season sugar development. Starch degradation appears to be delayed by water stress (Powell, 1976b; Ebel *et al.*, 1993), but generally water stress has led to earlier ethylene production (Lord *et al.*, 1963; Ebel *et al.*, 1993; Mills *et al.*, 1994; Mpelasoka *et al.*, 2000a). Water-core is more commonly related to maturity so differences in water-core may be expected in relation to the above effects on maturity (Marlow and Loescher, 1984).

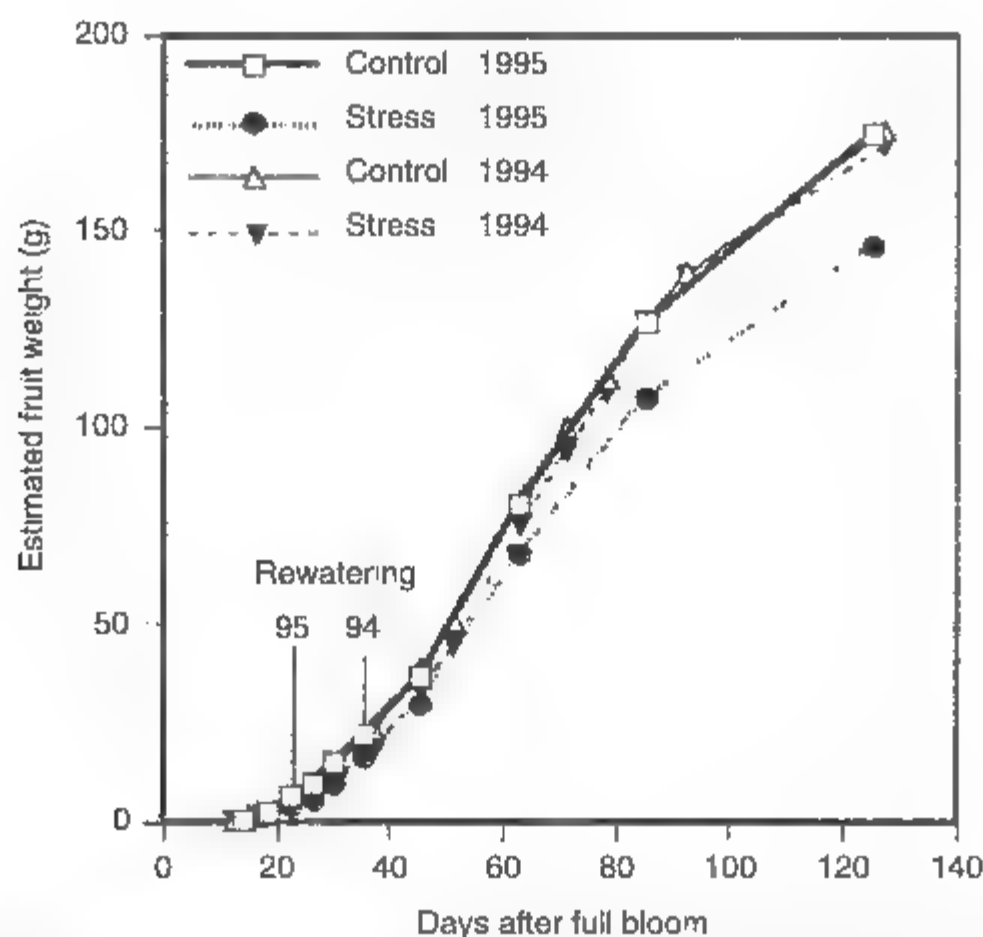


Fig. 8.6. Apple fruit growth as affected by short-term water stress during cell division (1995) or after cell division (1994) on seasonal fruit development (M. Al-Hazmi and A. Lakso, unpublished data)

The incidence of fruit disorders is quite variable in relation to water stress. Scald has been reported to be both increased in dry years but also decreased due to smaller fruit size caused by water stress (Wilkinson and Fidler, 1973). Lötter *et al.* (1985) found that scald was worse with early-season stress but decreased by late-season stress. Bitterpit and corking disorders have been reported to be both increased and decreased (Sharples, 1973; Goode, 1975; Lötter *et al.*, 1985). Since most calcium uptake into fruit occurs in the first several weeks of the growing season, it is likely that different timings of water stress may have different effects. Later-season stress that reduces final growth may reduce the 'dilution' of calcium concentration, so that the smaller fruits at harvest will have higher concentrations even though the total calcium per fruit may be similar. This effect was noted in a study of late-season European red-mite reductions of fruit size leading to fewer calcium-related disorders (Francesconi *et al.*, 1996). Clearly, a more fundamental understanding of these interactions of calcium, fruit growth and crop load is needed to be able to interpret the complex results from field studies.

8.7.4 Gas exchange

There have been a great number of studies of water stress on apple leaf photosynthesis and transpiration. The responses are typical of any crop in that with loss of turgor, stomata close and photosynthesis declines (Landsberg and Jones, 1981; Jones *et al.*, 1985; Lakso, 1994). An important characteristic of apple water relations is that mature leaves can osmotically adjust by as much as 2 MPa or more over time as stress develops in field trees (Goode and Higgs, 1973; Lakso *et al.*, 1984). The osmotic adjustment in mature leaves is primarily due to an accumulation of monosaccharides, especially sorbitol (Wang and Stutte, 1992; Wang *et al.*, 1995). The adjustment allows for turgor maintenance, which helps maintain gas exchange longer into a drought. Chlorophyll fluorescence has also been examined during water stress. Generally, it appears that initial or short-term stress responses are primarily related to gas exchange, but that, with longer drought periods, photochemical quenching is affected (Jones *et al.*, 1990; Massacci and Jones, 1990; Fernandez *et al.*, 1997b). Research has shown

that roots of young apple plants in drying soil appear to signal the top of the plant to reduce transpiration and leaf growth as if there was water stress, even though adequate water is available from the wet roots (Gowing *et al.*, 1990). How important such mechanisms are in the field still needs to be determined.

8.8 Integration of Water-stress Effects

Since most studies of water stress in apples have focused on only a few aspects, it is useful to attempt to integrate the overall effects, based on the format of Turner (1986). It evaluates avoidance mechanisms, tolerance by maintaining a high water potential, tolerance to low water potentials and finally tolerance to desiccation, which is rare in apple production and therefore will not be considered.

8.8.1 Drought avoidance or escape

The perennial nature, low-temperature threshold for spring growth and rapid rosette-type leaf development allows for significant canopy development before most stress can develop. This is important, as many early-season processes, such as initial fruit and shoot growth, are very sensitive to water stress.

8.8.2 Tolerance by maintaining high water potentials

The primary mechanisms of maintaining a high water potential within a plant are to: (i) reduce water loss by stomatal regulation, reduction of radiation absorption and reduction of leaf area; and (ii) maintain water uptake in spite of declining water availability by increased root growth and increased root hydraulic conductivity. Apple trees maintain high water potentials in both ways. The reduction in water loss in apple is accomplished by very good stomatal regulation, as discussed earlier. This leads to good overall WUE. As stress develops further, stomatal closure reduces transpiration and

there is a transpiration-induced adjustment in water potentials (see Fig. 8.1). To reduce radiation absorption and leaf area, apple trees initially reduce extension shoot growth directly with increasing stress. With further stress development leaves may eventually abscise, although mature leaves can osmotically adjust significantly to maintain turgor and function through moderate stress periods. To maintain water uptake with decreasing soil moisture or higher evaporative demand, apple trees have been shown to increase root hydraulic conductivity markedly in response to greater evaporative demands (Davies and Lakso, 1979a). Root growth declines in dry soil, but roots develop further in the wet zones of the soil, adjusting the water uptake pattern to optimize the use of soil water resources. Green *et al.* (1997) have also found that individual roots can adjust their water-uptake rates to be able to maintain total water uptake from those roots in wet soil.

8.8.3 Tolerance of low water potentials

The primary mechanism for tolerating low water potentials is the maintenance of turgor. Turgor maintenance in response to declining water potential requires osmotic adjustment to counter the decreasing total water potential. As water potential becomes more negative with drought stress, leaves of apple can lower the Ψ_s (i.e. it becomes more negative) by accumulating sugars and other solutes to maintain turgor and leaf function (Goode and Higgs, 1973; Lakso *et al.*, 1984; Jones *et al.*, 1985). Apple fruits also accumulate many solutes during development, which affect the fruit Ψ_s and fruit water relations. Additionally, the hydrolysis of starch to sugars as the fruit matures lowers the Ψ_s (i.e. it becomes more negative) without requiring imported carbohydrates.

Consequently, the overall strategy for apple response to water stress appears to be to reduce or stop leaf-area development (shoot tips do not osmotically adjust), maintain good WUE with stomatal coupling to photosynthesis and tolerate additional stress with osmotic adjustment of the mature leaves, fruits and

roots. Only with rather severe stress do apple trees abscise leaves. This strategy would appear to be best suited to shorter droughts or very deep rooting where some water would always be available. To make such a strategy effective, the function of the leaves that remain and osmotically adjust must persist to maintain canopy function, since new leaves are not continually produced. Apple leaves do have an exceedingly long functional life. Several studies have shown that the photosynthesis of healthy, exposed leaves is relatively stable for at least 5–7 months if the environment allows (Porpiglia and Barden, 1980; Fujii and Kennedy, 1985; Wunsche *et al.*, 2000). Such long leaf functional life allows the apple tree to maintain productivity with water stress while not producing new leaves continuously. In orchard conditions where extreme stresses are rare, this appears to be effective at maintaining productivity over a range of stress severity

8.9 Effects of Rootstocks on Apple Water Relations and Drought Tolerance

The effect of rootstocks on water relations would seem to be important and yet over many years of study and observation a clear picture has not evolved. This is probably due to the wide range of direct and indirect factors that may be involved. Consequently, the review of apple rootstocks by Ferree and Carlson (1987) only stated that MM.111 is reported to be the most tolerant to drought, while M.9 and M.26 are reported to be sensitive. A recent guide for rootstocks made little mention of drought resistance (Wertheim, 1998). Certainly, differences in tree response to water stress related to rootstocks can be observed in field situations. The difficulty lies in understanding the bases of these responses and whether they represent direct physiological effects or indirect effects.

8.9.1 Controlled drought-response studies

There have been several studies utilizing potted trees of varying age to give controlled water-stress treatments. Unfortunately, the

results have not been consistent. For example, M.9 has been reported to be less affected by drought than other stocks (Giulivo *et al.*, 1985; Fernandez *et al.*, 1997a; Kaynas *et al.*, 1997); however, other studies have come to the opposite conclusion (Chandel and Chauhan, 1990). Finally, Alleyne *et al.* (1989) found differences in diurnal stem potentials, but the differences were not related to stock-size category. Rogers (1939) summarized rhizotron observations and suggested that root growth slowed when soil water potentials fell below about 50 kPa; unfortunately, soil water potentials are rarely reported.

Physiological approaches have suggested that a good drought tolerance was correlated with higher levels of proline, abscisic acid and carbohydrates in the leaves of the scion, which were related to rootstock and soil moisture (Chandel and Chauhan, 1991). Again, the actual scion water status was not reported. Atkinson *et al.* (1999) found that all rootstocks they tested produced about 42 m of fine roots g^{-1} of root dry weight, but that dwarfing capability was not correlated with root production. Additionally, several of the stocks (including M.9, M.26 and MM.111) produced more fine roots in response to drought stress, while M.27 and several AR stocks generally produced fewer roots, but the responses to drought were not related to vigour control. Psarras and Merwin (2000) found a slight shift towards finer root diameter with water stress of M.9 and MM.111, but total root dry-matter production declined strongly and root respiration increased with soil moisture stress.

8.9.2 Water-relations studies in the field

The physiology and growth responses to normal field conditions or to drought stress in the field of trees on different rootstocks have also been evaluated. Some have found no or few differences in response to drought or irrigation by rootstock (Ferree and Schmid, 1990; Higgs and Jones, 1990). Shorter-term studies of diurnal patterns of stem potentials showed that non-stressed apple trees on M.9 and M.26 had more negative midday stem potentials than on M.7,

MM.106 or MM.104 (Olien and Lakso, 1986). Calculated hydraulic conductivities of xylem water transport suggest that rootstocks differ in their ability to conduct water to the scion. Tree size was well correlated with midday stem potentials in this group of stocks, and shoot expansion rate was directly related to midday stem potentials, which decreased with increasing vascular distance from the roots (A. Lakso, 1984, unpublished results).

8.9.3 Indirect effects

Apple rootstock root systems have very low root-length densities (root length per volume of soil), have non-uniform distributions and differ in their responses to soil structure (Rogers, 1939; Fernandez *et al.*, 1995). Consequently, root distribution and density patterns as affected by rootstock in any given soil will determine the total volume of potentially available soil water and determine the availability of water independently of any direct physiological response of the rootstock itself. Rootstock interactions with scion growth and cropping also complicate such studies. Rootstocks differ in their tendency to induce cropping, especially early cropping in young orchards (Wertheim, 1998). As discussed earlier, cropping has strong effects on water use per unit leaf area, and the growth of the root system is strongly inhibited by heavy crops. Hewett and Cassidy (1977) and Goode *et al.* (1978) found that irrigation gave stronger effects in heavily cropping trees (e.g. the 'on' years of a biennial orchard).

Finally, many studies have been done with young potted rootstocks or trees grafted on different rootstocks. Since rootstock breeders feel that at least 6 or 7 years of growth in the field are required to establish a stable ranking of rootstock vigour, a correlation of mature field behaviour with that of young potted trees may not necessarily be expected. Indeed, many of the studies reviewed reported plant-size rankings that were not in accordance with mature size ranking. Also a 'drought treatment' only means that water was not applied; it does not mean that the same plant water status

was attained. Potted-tree studies may induce variable responses to water withholding that are due primarily to variable depletion of a constant pot soil volume by trees with different leaf areas. Considering all the complexities mentioned above, it would be desirable for future studies to relate responses to estimates of either soil or plant water status, such as predawn water potential or midday stem potential (Olien and Lakso, 1986, Alleyne *et al.*, 1989). This will help to differentiate the effects of stress due to root distribution or plant size (in relation to soil volume) versus internal effects, such as hydraulic conductance or hormone balances.

This author proposes that, under field conditions with a non-restrictive soil, there is probably a greater midday water stress induced under high transpiration rates in the more dwarfing stocks, due to lower hydraulic conductivity compared with the more vigorous stocks. As the summer becomes warmer, the shoot growth of the more dwarfing stocks terminates earlier (R.S. Johnson and A. Lakso, 1982, unpublished results). For the more vigorous stocks, shoots can then grow more until the length of the branches reaches a length where the total hydraulic resistance (the rootstock plus the resistance of flow in the branch) is similar to that at the end of the shorter branches on the dwarfing stocks. This would explain why the summer leaf water potentials and stomatal conductances are generally similar for exterior leaves of a scion on many different rootstocks (as also noted by Ferree and Schmid (1990) over many rootstocks). It may also explain why apple trees, and other tree species, tend to stabilize at a spherical form, where all exterior shoot tips are similar distances from the root crown.

8.10 Management of Water Relations in the Field

8.10.1 Orchard water balance

To manage the water balance of an apple orchard requires knowledge of water use over the season in the given climate, the water status needed for the desired tree per-

formance, and other factors affecting the water balance of an orchard (rainfall, soil reserves, climate, cover crops and cultivar). In arid climates, the rainfall and soil reserves are generally so deficient compared with ET demands that the decision to irrigate is clear. However, in humid climates, lower ET demands and greater rainfall totals and variability make it difficult to determine the economic feasibility of irrigation. In this case the best approach is a risk assessment for water limitations. This should include the soil reserves (soil rooting volume, soil water-holding capacity and initial water content in the spring), the average rainfall, the average tree demands and the demands of any competing plants such as cover crops between the rows (common to reduce erosion in high-rainfall areas). In some cases adequate water status may be obtained in dry seasons simply by reducing water use of competing plants with herbicides. A quantitative risk analysis is very useful; however, it is beyond the scope of this review.

8.10.2 Irrigation management

Irrigation is primarily to provide supplemental water not provided by rainfall or soil water reserves. Consequently, efficient irrigation management requires knowledge of the water loss of the apple orchard (trees, soil evaporation and cover crops/weeds) and the soil water reserves and rainfall. There are several practical approaches used to estimate water usage or tree water status for scheduling irrigation applications.

8.10.2.1 Experience

A very common qualitative approach is a 'mental model', which is essentially a risk assessment based on grower experience with the lengths of droughts and evaporative demands in relation to the perceived soil water reserves and their irrigation tools. Although not quantitative or documented, a good grower is able to take into account a wide range of unique characteristics of their individual orchards that general models cannot accommodate.

8.10.2.2 Soil-moisture monitoring

Another common approach is to monitor soil moisture with various soil-moisture devices and relate soil moisture to plant water use and plant stress (for reviews of measurement of soil moisture, see Campbell, 1988; Ley, 1994a; Hanson and Peters, 2000; Hanson *et al.*, 2000). Since the soil water content is measured, these methods are good for determining soil water depletion, which is needed to estimate whole-orchard ET and irrigation needs.

The greatest general limitation with soil-moisture monitoring is sampling in heterogeneous soils in which there are extremely low root densities and erratic apple root distributions. Even in quite uniform soils, it is difficult to determine where to place a limited number of sampling sensors or access sites, since it is difficult to know where the roots are located, especially for dwarfing rootstocks. Due to this problem, soil-moisture monitoring is best suited to developing orchard water-use estimates with soil water-balance studies, rather than to estimating plant water status.

8.10.2.3 Evapotranspiration estimations

Another common approach is to estimate the environmental demands for ET as modified by orchard architecture and plant resistances for water vapour. There have been many studies of microclimatology and the factors that drive ET and many equations developed to estimate ET. The recent Food and Agriculture Organization (FAO) book (Allen *et al.*, 1998) is an extensive review of this area and is recommended for study, while Hanson *et al.* (1999) is more grower-orientated.

In general, the major environmental factors are net radiation (R_n), humidity and temperature, which lead to vapour-pressure deficits (VPD), and wind speed, which affects the boundary-layer resistance around the crop. Crop characteristics generally affect ET by affecting the boundary-layer resistance (canopy height, aerodynamic roughness and density), the radiation energy balance (reflectivity and

ground cover or light interception) and the stomatal resistance to water loss. There are important interactions among these factors. These factors have been summarized in several models of ET, which are similar in that they incorporate these main factors with various simplifying assumptions. The model most commonly used is the original or modified Penman-Monteith equation (Allen *et al.*, 1998)

One important characteristic unique to tall, discontinuous canopies like apple orchards is that the tall, rough canopies cause air turbulence, which reduces crop boundary-layer resistances. This means that the tree canopies are well coupled to the bulk atmosphere above (Jarvis, 1985). Consequently, in apple trees the stomatal resistances are important regulators of ET, since transpired water vapour quickly moves to the bulk air and the VPG is not affected. This is different from low, smooth, continuous crops like grasses, which can develop a thick boundary layer that traps humidity. If the grass stomata open, the transpired water vapour cannot escape, so the VPG declines, counterbalancing the opening of the stomata. Thus, grass-crop ET may not respond significantly to changes in stomatal resistances (McNaughton and Jarvis, 1983; Jarvis, 1985; Jones, 1992; Fig. 8.7). Consequently, apple tree ET is controlled by R_n , VPG and stomatal conductance, while grasses or cover crops between the rows of apples respond primarily to R_n (Plate 8.1).

8.10.2.4 Crop coefficients for irrigation

Since complete ET analyses to determine absolute ET cannot easily be done with all crops in all climates, a method has been developed where individual crop ET is related to a reference crop or to another common measure, such as class A pan evaporation (E_{pan}). A healthy, low grass is typically the reference crop, since the ET of grass has been studied extensively and over extended periods and is well estimated from meteorological data by the modified Penman-Monteith equation (Allen *et al.*, 1998). This reference is called ET_o or ET_{grass} . In contrast, apple-crop ET

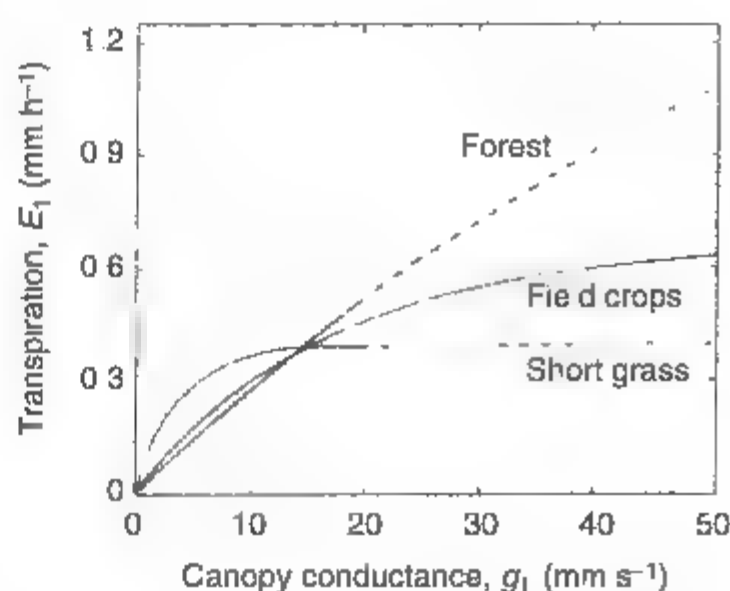


Fig. 8.7. The general response of crop transpiration to canopy conductance comparing low grass, field crops and forest (from Jones, 1992, with permission).

has been estimated from fewer studies, but apple ET has been related to the grass reference ET by a scaling factor called a crop coefficient (K_c) (Ley, 1994b; Allen *et al.*, 1998; Hanson *et al.*, 1999). Weather data are used to calculate the reference grass ET, which is then multiplied by a crop coefficient to adjust for crop differences

$$\text{Apple ET} = ET_{grass} \times K_{c \text{ apple}}$$

Similarly versus E_{pan} :

$$\text{Apple ET} = E_{pan} \times K_{c \text{ apple/pan}}$$

Basal crop coefficients have been estimated with the assumption for fruit-trees of 60% ground cover, no water stress, a large continuous orchard and a moderate climate (Allen *et al.*, 1998). There are several corrections or adjustments that have been developed that are appropriate for apple orchards, though not easily applied due to the erratic canopies and alleys (Allen *et al.*, 1998).

Corrections are made for the seasonal development of the apple canopy and thus variations in seasonal water use (Fig. 8.8). Additionally, the crop coefficient for apple orchards is affected by other factors that affect tree water use. First, due to the discontinuous canopies, ground coverage is used as a simplification for light interception, the driving energy. Mature orchards are assumed to be about 60% ground cover, giving full ET (Ferreira and Goldhamer, 1990; Hanson *et al.*, 1999). Apple orchards

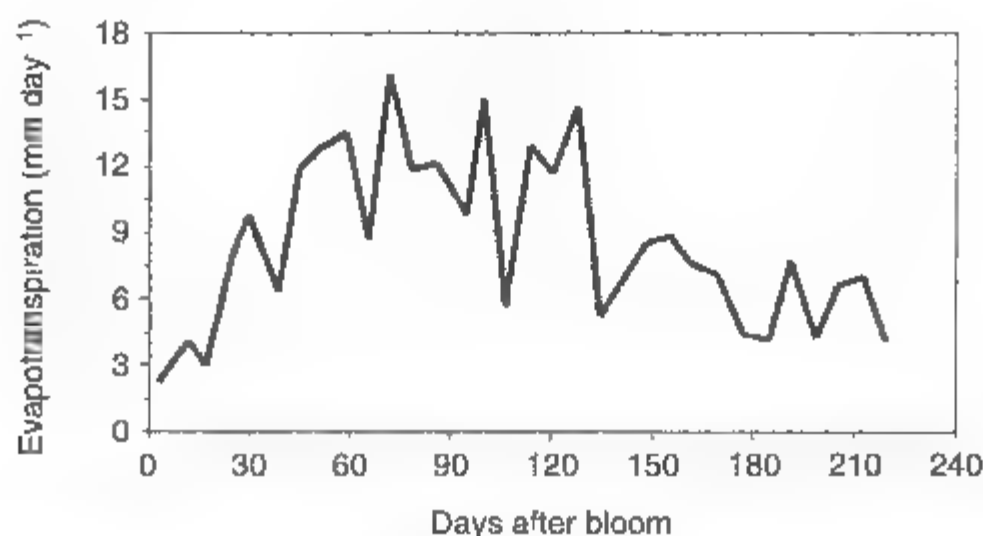


Fig. 8.8. Seasonal pattern of apple-orchard water use (from Beukes and Weber, 1982, reproduced by permission of the *Journal of Horticultural Science*)

vary in mid-season ground coverage, since so many canopy forms are used. This author has found light interception of mature commercial orchards to vary from about 25% to about 80%. The mid-day ground-cover estimate has been found to be useful for horizontal to fairly natural round trees, but it underestimated daily light interception for slender spindle and thin, vertical palmette forms by 14 and 35%, respectively (Wunsche *et al.*, 1995)

Corrections are also based on differences in humidity and wind in different climates, and the differences are accentuated with tall crops, such as apple orchards (Allen *et al.*, 1998). For example, in arid climates with low humidity, the K_c for tall crops and for higher wind speeds must be increased as much as 30% for 5 m tall apple trees with 6 m s⁻¹ average winds. In contrast, in humid climates with calm winds, the K_c must be decreased by 20–25%. This indicates, for example, that, for apple trees and other tall crops, K_c values developed in arid climates (where such studies are usually done) may not be correct in more humid climates, where many apples are produced (Annandale and Stockle, 1994)

Additional adjustments that are made relate to: (i) edge effects, called 'clothes-line' or 'oasis' effects, for small plantings that are adjacent to different sizes or types of vegetation; (ii) lower stomatal conductances than are normally assumed for the grass; (iii) reductions in stomatal conductance due to

drought or other stresses (crop-load effects, for example); and (iv) differences between orchards with a cover crop between the rows versus those with bare soil (Allen *et al.*, 1998). Clearly, it is not possible to provide simple guidelines to estimate the ET of apple orchards, due to the myriad of climates, trees and adjacent environments.

Consequently, it is highly desirable to do local studies of water use in each climatic region to determine local K_c values, rather than accepting K_c values from other regions.

8.10.3 Plant-based methods for irrigation scheduling

The many indirect methods discussed are limited to general guidelines or values, since there are so many unique combinations of environmental and soil conditions. These may be adequate for scheduling irrigation, but, in intensively managed orchards, more direct methods to allow the tree to provide information on water needs have been desired. The bases of most of these methods have been reviewed earlier in the section on measurement of tree water status

8.10.3.1 Visual inspection

The most common method is visual inspection of the trees for signs of wilting, growth inhibition, leaf colour, etc. Although these symptoms indicate stress, usually they appear too late to make an early intervention.

8.10.3.2 Midday stem potential

The midday stem potential is a very good integrator of water status at any time and has been well related to important crop processes, as reviewed earlier. Although the midday stem-potential method is feasible for large growers with qualified technical support or consultants, the use of the pressure bomb is still considered too technical for most growers.

8.10.3.3 Temperature monitoring

As discussed earlier, monitoring leaf temperature has been used to estimate when plants need water. However, the responses of apple stomata to other factors, such as crop load, may give false signals, (Jones, 1994, 1999a,b). Also the dynamics of variable radiation, VPD and wind makes it difficult to use temperature monitoring in many humid or cloudy climates. Jones (1999a) has suggested using wet and non-transpiring leaves as references instead of air temperature, but the dynamic variability and the cost of the instrument will limit its use. Though not quantitative, the simple method of feeling the warmth of the largest leaves in the sun with one's fingers should be used more as an indicator of stomatal closure, as it is more sensitive than one may think and many trees can be checked easily and quickly.

8.10.3.4 Trunk and fruit monitoring

As discussed earlier, the physical contraction of the stems and fruit of apple trees has been examined as an integrator of water stress. This method is promising, but it needs calibration to determine thresholds for initiating irrigation and needs more rugged and inexpensive equipment.

8.10.4 Deficit irrigation with apples

In many regions water may be limiting or expensive, so there has been much interest in improving efficiency of irrigation by using irrigation at levels below the water

use demands of the trees (i.e. at a deficit). The term regulated deficit irrigation (RDI) implies the same concept, except perhaps with the targeting of specific growth stages versus full-season deficits; the general term deficit irrigation will be used here. Behboudian and Mills (1997) have recently reviewed deficit irrigation, so this discussion will address how it may apply in apple production.

In addition to saving water, the use of deficit irrigation at critical times during crop development has been tested to control vegetative growth without harming fruit development (Chalmers *et al.*, 1981) or to improve apple fruit quality (Mpelasoka *et al.*, 2000a). A key point was to identify a stage of development when the fruit were not actively growing or not sensitive to stress, but the shoots were still active. This occurs in stone fruit and grapes, which have a double-sigmoid fruit-growth pattern with a mid-season lag in fruit growth while shoots are still vigorous. This scenario does not occur with apple, since the inherent fruit-growth pattern by weight is best described as 'expolinear' (exponential early, then close to linear until normal harvest) (Lakso *et al.*, 1995). Although apple extension shoots may be sensitive to water stress, fruit growth is also quite sensitive, especially in the early season when shoot growth is strong (Fig. 8.9). Therefore, managing deficit irrigation to avoid loss of fruit growth seems much more difficult in the field with apples than with stone fruit or grapes.

Studies of deficit irrigation in apples have shown that there are variable reductions in fruit weights with deficit irrigation in the field (Beukes and Weber, 1982; Lötter *et al.*, 1985; Ebel *et al.*, 1993, 1995; Mills *et al.*, 1994, 1997; Kilili *et al.*, 1996a; Naor *et al.*, 1997; Behboudian *et al.*, 1998; Mpelasoka *et al.*, 2000a; Fig. 8.10). Reductions in fruit size may not necessarily be detrimental if fruit size normally tends to be too large for optimal quality. Conversely, reductions in fruit size may be doubly detrimental for heavily cropping trees, since fruit size is already reduced by the crop load.

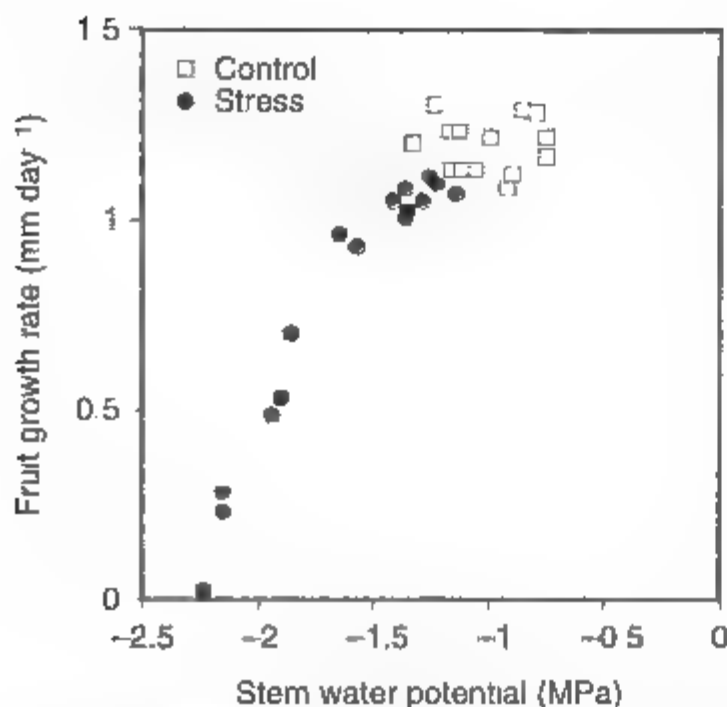


Fig. 8.9. Apple fruit growth rates as affected by varying stem water potentials induced by water stress (M. Al-Hazmi and A. Lakso, 1996, unpublished data)

In conclusion, it appears that deficit irrigation can be somewhat useful, but the apple growth habit is not particularly well suited to this approach, especially in climates with summer rainfall. For control of vegetative growth, the early-season use of gibberellin inhibitors, such as paclobutrazol or prohexadione-Ca, are probably better tools for that purpose.

8.11 Needs for Integrative Approach to Water Relations

From the preceding discussion, it is clear that a broad integrative view is necessary to be able to interpret results, especially from the field. The lack of adequate information on the environment, tree age, stage of tree development, crop load, soil type and related information was the major limitation in evaluating the many publications in this area.

8.11.1. Modelling water relations

Modelling is an approach that attempts to quantitatively integrate the main controlling factors in a system over time. There have been several aspects of apple water relations

modelled, but no overall model has been developed. Landsberg and colleagues began to include water relations in a general apple model, but the model did not appear to have been completed (Landsberg, 1980). Models of stomatal response to the environment have been developed (Landsberg and Butler, 1980; Thorpe *et al.*, 1980; Jones and Higgs, 1989; Jones, 1998), with an emphasis on the effects of VPD reducing conductance. This has recently been expanded to scale up for whole-tree transpiration estimates (Green and McNaughton, 1996). Hydraulic flow and capacitance of the tree have been modelled with electrical-circuit analogues (Landsberg *et al.*, 1976; Jones, 1983). Perhaps the most useful modelling has been in regard to evapotranspiration of orchards (Butler, 1976; Thorpe, 1978; Thorpe *et al.*, 1978; van der Maas, 1992; Green and McNaughton, 1996), which has used the energy-balance approach (see Section 8.10.2.3). However, validation of these models with independent data from different climates is needed.

Models allow quantitative hypotheses to be developed that can be tested, but they have limitations that must be considered in relation to the unique characteristics of apple trees. Jones and Tardieu (1998) make several important points relevant to modelling water relations of apples: (i) models are best in homogeneous systems (apple canopies and root systems certainly are not), (ii) modelling water status in soils is difficult due to increasing spatial variability as the soil dries; the low root density and clumping of apple roots are a problem; (iii) modelling stomatal control of water relations is complicated by non-hydraulic factors that affect stomatal conductance, such as crop effects in apple; (iv) rainfall interception by canopies may be an important component of orchard water balance and yet we lack information on rainfall interception; and (v) uniform canopies are easiest to model; apple canopies have great variability due to various training systems. So modelling apple-tree water relations will be a difficult challenge.

Finally, a precautionary note is needed. Most physiological studies of apple are done to address applied problems of stress in the field and yet too often small, potted apple

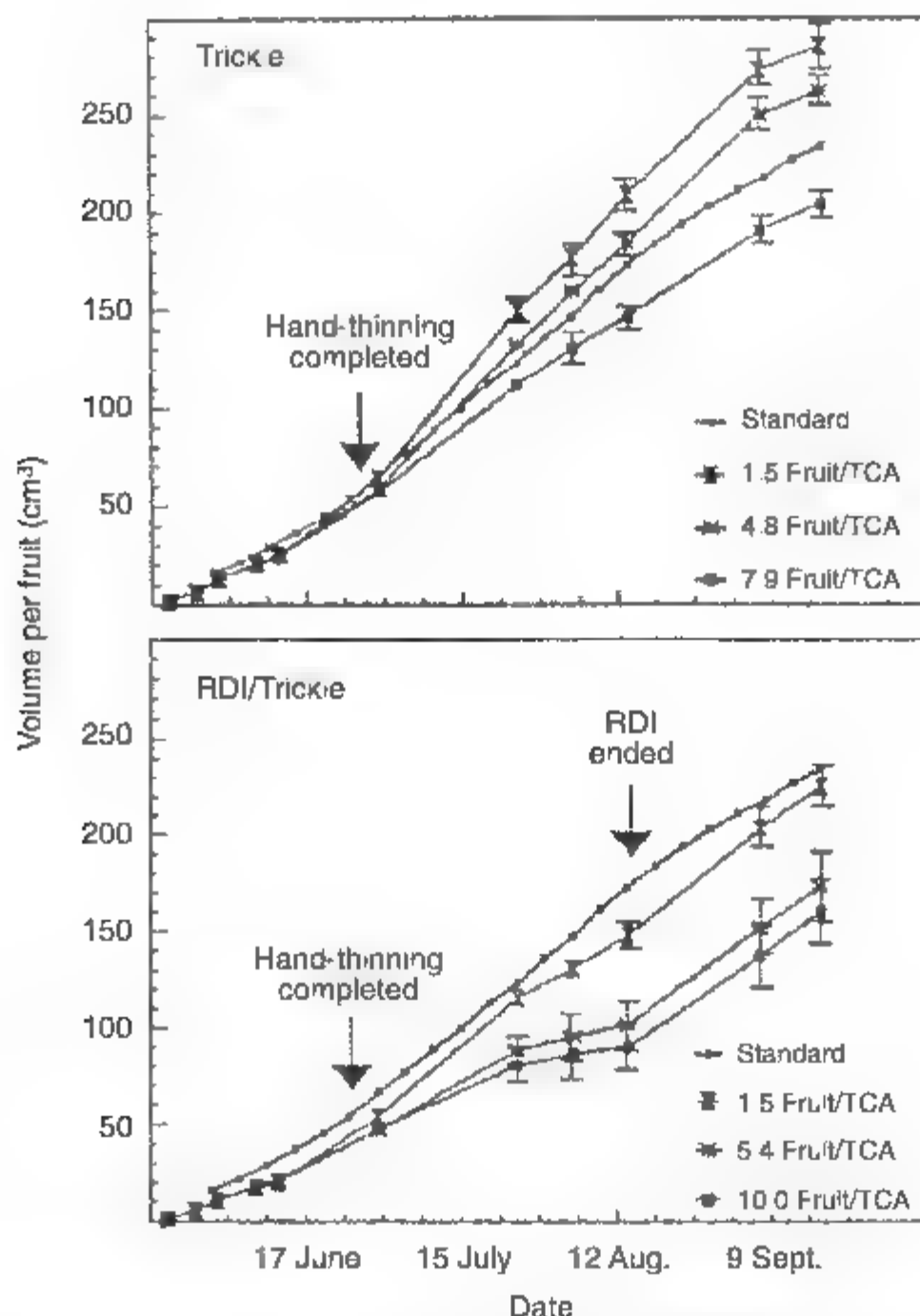


Fig. 8.10. Apple fruit growth over time of varying crop loads with full irrigation (top) and with mid-season regulated deficit irrigation (from Ebel *et al.*, 1995). The 'standard' curve is the expected curve for normal crop levels in Washington State. TCA, trunk cross-sectional area in cm^2 .

trees are used as model systems under controlled or semi-controlled conditions. Are they a good model of the mature tree behaviour? In the case of water relations, there are so many differences in the environment of the pot versus field soil and the tree behaviour that we cannot assume that potted trees are a good model. We must accept the challenge of working in the field with mature plants.

8.12 Conclusions

In conclusion, the water relations of apple trees are extremely complex and dynamic, with many soil, atmospheric, temporal,

structural, physiological and cultural factors interacting. It is impossible to understand these relations with a reductionist view, although detailed understanding of component processes is always valuable. We must strive to develop a broad integrative approach in which many observations are taken in concert with measurements. Although more difficult experimentally, it appears that we shall need to utilize plant-based measures to integrate all the factors involved, since indirect measures, such as soil moisture or climate, are inadequate. Midday stem water potentials are probably the best single physiological measure of plant water status; however, better integrals

of water stress are needed. Finally, the role of modern molecular biology is potentially exciting but not clear at this time. For example, recent discoveries of aquaporins that affect membrane hydraulic permeability may be important, but the relevance to field

water relations of apple trees will need to be determined (Tyerman *et al.*, 1999). It will certainly require good teamwork and cooperation across disciplines to evaluate how best to use these new tools to improve our understanding.

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9 Light Relations

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9.1 Introduction

Visible light in the 400–700 nm waveband is the driving factor of biomass production via its effect on photosynthesis, so it is not surprising that production of dry matter in apple has been shown to be related to the amount of visible light intercepted by trees (Palmer, 1989; Lakso, 1994). However, in fruit trees, including apple, dry-matter production does not automatically translate into increased yield of marketable fruit. The complex phenomena that result in the parti-

tioning of resources (such as nutrients, carbon and water) into fruit instead of other organs are also largely controlled by light. Light therefore plays a twofold role in influencing the processes that lead to the production of large quantities of high-quality fruit: on the one hand, it supplies the energy stored in chemical form in carbohydrates; on the other, it influences the ontogeny of the tree's structures, so that the tree's physiological traits are generally enhanced in parts of the canopy where high light conditions prevail

This influence extends to many morphological and physiological traits of the vegetative components of a canopy, from bud differentiation to leaf attributes, to the ratio of spur vs. shoot leaf area, to the photosynthetic potential of these leaves and to the photosynthetic capacity of the different leaf types that support fruit growth. Furthermore, the duration of the light period and light intensity each affect partitioning of carbon between different chemical forms (transport or storage) and between reproductive and vegetative sinks and affect fruit quality attributes, such as skin colour, soluble-solids concentration, acidity and the incidence of storage-related disorders.

Because of these many effects of light, knowledge of the basic relations between light and the tree is necessary to manage the canopy in order to maximize its production efficiency. This chapter is concerned with examining the main aspects of tree light relations, beginning with a definition of the main physical characteristics of light, leading to an examination of several physiological aspects and then deriving practical aspects of tree and crop management that have their foundation in this scientific knowledge.

9.2 Light: Physical Properties

The irradiance (total radiant flux density) provided by the sun that reaches the outer atmosphere, measured perpendicularly to it, is termed the 'solar constant' and its value is on average 1360 W m^{-2} . However, because of absorption by the atmosphere, the total radiant flux reaching the ground at sea level is about 58% of that value. If the whole spectrum of short-wave (wavelengths $< 4 \mu\text{m}$) radiation is considered, the total energy available (global irradiation) is approximately 800 W m^{-2} at sea level. Global irradiation increases with altitude, although its actual values will depend on clouds and atmospheric composition, since water vapour, CO_2 , gases and dust particles absorb and scatter radiation at different rates. Under clear sky conditions at noon, more than 1000 W m^{-2} can be found at 2000 m above sea level (Nobel, 1983), with a greater fraction in the UV component than occurs at sea level.

Visible light represents a fraction (about 42–45%) of the short-wave radiation spectrum released by the sun. Because photosynthesis is by far the most important plant phenomenon influenced by light, this portion of the spectrum is also termed photosynthetically active radiation (PAR). The definition photosynthetic photon flux (PPF) is also appropriate, to indicate that the photosynthetic process responds to the rate of absorption of photons intercepted in this range and not to the rate of absorption of energy. PPF has units of $\mu\text{mol m}^{-2} \text{ s}^{-1}$ (micromoles of quanta of energy, i.e. of photons, per unit area and time). A typical PPF value for the direct component of sunlight at noon on a clear day with the sun overhead is approximately $2000 \mu\text{mol m}^{-2} \text{ s}^{-1}$.

In addition to direct irradiation from the sun, two other light fractions contribute to the total amount of energy available on the ground: a fraction scattered by the clouds and a fraction scattered by the atmosphere, which together make up the diffuse irradiation component. On a cloudy day, diffuse irradiation can be quite high relative to the direct component. Because diffuse irradiation can penetrate the canopy from virtually every direction, the total light available in inner tree-canopy positions will be affected by the relative amounts of the direct and diffuse components: under western New York State conditions, Lakso and Musselman (1976) found that the quantity of light available at locations inside a canopy was increased under partly cloudy conditions, compared with that under clear sky conditions (Fig. 9.1).

Latitude affects the average annual amount of light available daily – higher latitudes have lower mean daily light integral values. The disadvantage due to latitude is partly offset by the longer daytime duration during the summer at the higher latitudes.

Both the intensity and the spectral distribution of light after it reaches the canopy change dramatically within a short distance. Absorption by leaves averages about 80% of incoming visible light. A major portion of the 'missing' light is in the region of 550 nm, where chlorophyll absorption is low, and a large fraction of this light is reflected

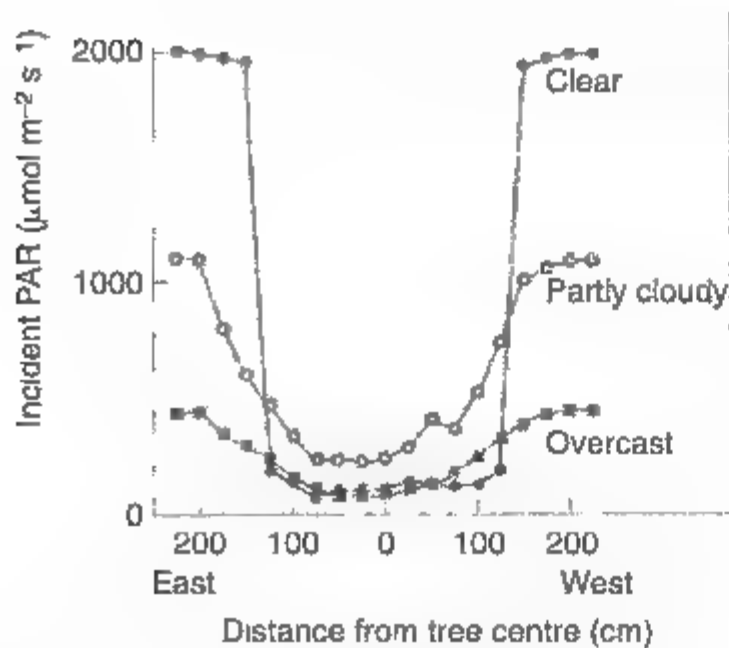


Fig. 9.1. The penetration of light within the canopy of a 9-year-old 'Golden Delicious'/M.2 tree, during 3 days with different sky conditions. The greater penetration to the interior parts of the canopy occurred on the day with the highest diffuse radiation component (the partly cloudy day). PAR, photosynthetically active radiation. (From Lakso and Musselman, 1976, reprinted with permission.)

or transmitted, leading to the green colour of leaves. A rather large fraction of the energy load on the leaf is from infrared (IR) radiation from the sun or from the atmosphere, but it is in large part re-emitted at longer wavelengths (about 70% of the total irradiation is lost this way (Nobel, 1983)). The spectral composition of the light within a canopy is thus changed, with a shift towards longer wavelengths brought about – in the visible range – by the selective absorption of the photosynthetic pigments (particularly effective in reducing the blue and red components) and by lower absorption and greater reflectance in the IR. As a result of this, the red/far-red ratio in the inner regions of the canopy is reduced, which may result in changes in phytochrome-mediated responses. However, very little is known regarding the relevance of phytochrome in apple morphogenetic responses. Indeed, many examples exist in the literature where responses generally attributed to phytochrome (leaf morphology and photosynthetic characteristics, flower-bud differentiation, fruit growth and colour) have been induced by simply reducing light levels with neutral-density shade

cloth, which, unlike natural within-canopy shading, does not alter the light spectrum.

9.3 Photosynthesis

The major quantitative effect of light on plants is on photosynthetic activity: in properly managed orchards, increases in photosynthesis (i.e. light intercepted) will result in increases in yields of marketable apples. The most light-efficient orchard configurations have been reported as being capable of intercepting 60–70% of available radiation, which may translate into very high yields – maximum yields reported are from New Zealand, at 120–140 t ha⁻¹ year⁻¹, sustained over several seasons (Lakso *et al.*, 1999). Several authors have demonstrated the relationship between light interception and yield, as summarized by Lakso (1994), who also showed how, at light interception levels greater than 50% of available light, orchard productivity may differ widely, from very poor to very high yields. A partial reason why this may be so lies in the curvilinear relationship between PPF and whole-tree photosynthesis (Fig. 9.2): in the absence of other limiting factors, when the light intensity available to the canopy exceeds saturation (the light intensity above which no further increases in photosynthesis occur), the tree's instantaneous potential is reached and no further photosynthetic gain will be obtained by further increases in light interception.

The light-response curve of a canopy, as shown in Fig. 9.2, generally resembles that of a single leaf. Depending on the canopy characteristics (size, density, degree of shading of interior leaves by the external ones), however, the values of the compensation point, the quantum efficiency and the saturation point (Flore and Lakso, 1989) for a single leaf and for a whole canopy may vary widely. The greater the density of the canopy and the amount of shaded leaves, the greater the discrepancy between single-leaf and whole-canopy measurements: in general, since the whole-canopy gas exchanges normally include fruit and wood respiration in addition to respiratory losses from the leaves, the com-

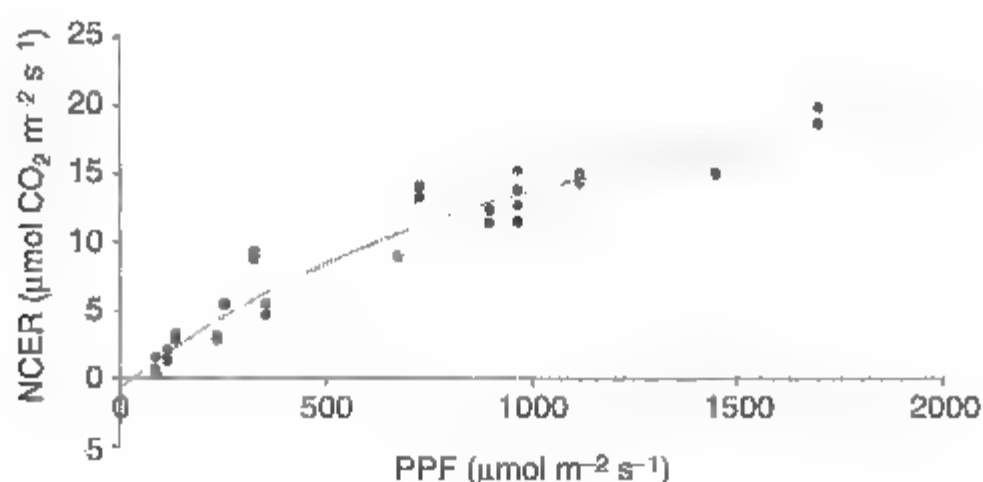


Fig. 9.2. Light-response curve of a 7-year-old 'Golden Delicious' tree, enclosed in a whole-tree assimilation chamber. The tree was progressively shaded by adding layers of neutral-density shading cloth. NCER, net carbon exchange rate; PPF, photosynthetic photon flux.

compensation point is higher for the whole canopy. At the whole-canopy level, the interaction with light is more complex, as it integrates many factors in the response, including, in addition to those outlined above, tree shape, leaf density, crop load, nutritional factors and water status. However, a whole-tree approach solves the problem of scaling-up individual leaf measurements, in order to estimate a tree's response. Because of these differences, both single-leaf and whole-canopy responses are discussed.

9.3.1 Single leaves

Apple leaves exhibit a typical asymptotic response of photosynthesis to PPF and their photosynthetic parameters – compensation, saturation and quantum efficiency – are comparable to other major temperate fruit crops. Apple-leaf morphology exhibits distinct traits that identify the light environment under which the leaf differentiation processes have taken place and which relate directly to leaf productive potential. In fact, leaves that have developed in the exterior, well-illuminated parts of the canopy ('sun' leaves) are capable of greater maximum photosynthesis than leaves that have been under low photon fluxes during their development ('shade' leaves). However, shade leaves are in general more efficient at utilizing low photosynthetic photon fluxes or the sun flecks that may occur in the internal portions of a canopy. This differentiation is largely irre-

versible: once a shade leaf is placed under high photosynthetic photon fluxes (as a result of summer pruning, for example), it is not capable of reaching the same high rates of fixation that can be reached by sun leaves.

Sun leaves exhibit greater thickness (related to the number of layers of cells in the palisade parenchyma (Doud and Ferree, 1980b)). They also have higher nitrogen content and are more dense (higher leaf-area density (mg cm^{-2})) than shade leaves (Flore and Lakso, 1989). The photon fluxes during leaf emergence and development at the beginning of the season influence these parameters, which, once set, do not vary considerably. This constitutes one of the main reasons for maintaining open canopies with good light distribution throughout the season. In addition to the effect of the current light levels on leaf characteristics, some evidence exists that the light levels experienced by the bud during the differentiation process in the previous season may influence parameters such as specific leaf area, at least for the primary spur leaves. Tustin *et al.* (1992) reported lower specific leaf area 2 weeks after full bloom (AFB) in primary spur leaves derived from buds that had differentiated under low PPF in the previous season, even though at 2 weeks AFB they were fully illuminated (Table 9.1). In the same study, the bourse shoot leaves responded only to current light levels: severe shading (70% reduction) of leaves in high light positions significantly decreased leaf-area density

Table 9.1. Leaf area density ($\text{mg dry matter cm}^{-2}$) of spur and bourse shoot leaves growing under different light regimes at 2, 5 and 8 weeks after full bloom, on 9-year-old 'Golden Delicious'/M 9 trees (with permission from Tustin *et al.*, 1992)

Light regime ¹	Weeks after full bloom					
	2		5		8	
	Spur	Bourse	Spur	Bourse	Spur	Bourse
Full sun	7.4 a ²	6.3 a	7.6 a	7.0 a	7.7 a	7.9 a
Shade cloth	6.1 b	5.2 b	7.0 b	5.7 b	6.1 b	6.0 b
Natural shade	6.4 b	6.0 a	6.2 c	5.3 b	6.2 b	5.5 b

¹ Light regime as follows: full sun, external canopy positions, continuously in high light conditions; shade cloth, as full sun, but shaded to 70% shade with neutral density shade cloth for 1 week; natural shade, internal canopy positions, undergoing natural shading as the canopy fills in.

² Mean separation within columns by SNK test; $P = 0.05$

within 1 week. Therefore, if a bud either differentiates or develops under low photon fluxes, it may produce leaves that inherently have lower intrinsic photosynthetic potential, with ensuing decreases in the tree's productive potential – and the same will occur under conditions that develop within a quickly closing canopy.

9.3.2 Whole canopy

Because different training systems have different light-interception profiles during the day and because orchard light interception is affected by orchard design (a combination of tree shape, dimensions and tree arrangement within and between rows), it is very important to study the gas exchange rates of entire trees in the field over extended periods (Plate 9.1). However, while measurement of single-leaf photosynthesis in the field has become fairly easy because of the availability of relatively affordable commercial units, at the whole-tree level progress has been slower, mostly because of a lack of commercial units, which has forced researchers to build their own instrumentation – often based on adaptations of single-leaf units (Corelli Grappadelli and Magnanini, 1997).

Current whole-canopy techniques pose specific methodological problems, which have limited the number of studies performed. One of them is that, to express gas

exchanges on a leaf-area basis (specific rates), in analogy to single-leaf determinations, it is necessary to measure accurately the leaf area and the profile of photon fluxes to which individual leaves are exposed within the canopy. Tree leaf area is rather difficult and time-consuming to measure, even though several methods have been evaluated for its estimation (Wunsche and Palmer, 1997a). An alternative approach is to express tree gas exchange in terms of the light intercepted by the canopy (i.e. in PPF units), under the assumption that most of the intercepted light is absorbed by the tree (i.e. that reflectance and transmittance are negligible). This assumption is normally valid, since leaves absorb, on average, 80% of the energy associated with the visible spectrum.

Tree photosynthesis is a function of the amount of light intercepted, but it may also be influenced by the time of day when maximum light interception is attained, because of the influence of temperature on photosynthetic activity and also of other physiological determinants. The complexity of the response is demonstrated by the typical daily pattern of photosynthesis for a young (second leaf) north-south (N-S)-orientated apple hedgerow (Fig. 9.3): a rather sharp increase in rate in the morning hours is followed by a slow tapering off, despite the fact that light interception in the afternoon on the western side parallels the interception in the morning hours on the eastern side (L. Corelli Grappadelli and G. Costa, 2001, unpublished results).

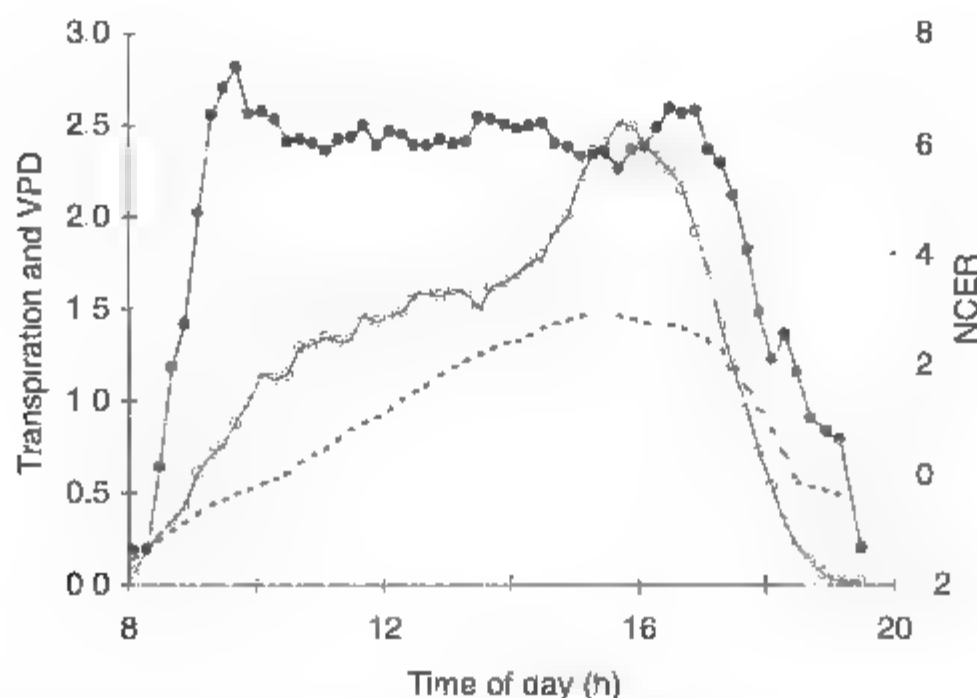


Fig. 9.3. Diurnal pattern of the gas exchanges of a 2-year-old 'Gala/M 9' apple tree, trained as a slender spindle, in a N-S row, and of the vapour-pressure deficit (VPD), during a clear day in September. While the carbon exchange (●) peaks in the morning hours and slowly tapers off, the water loss (○) increases in the afternoon, following the pattern of the VPD (-----). Transpiration has units of mmol H₂O per tree s⁻¹, VPD is in kPa, net carbon exchange rate (NCER) has units of μmol CO₂ per tree s⁻¹. (L. Corelli Grappadello and G. Costa, 2001, unpublished.)

Thus, if the daily pattern of light interception is different among training systems, so should be the photosynthetic response. It is reasonable to expect differences between the opposite sides of a palmette or central axis hedgerow, as opposed, for example, to a Y-trellis. It is known that Y-trellis orchards exhibit higher light interception than hedgerows or large central-leader trees. Row orientation will also have an impact. While data on tree net carbon exchange (NCE) as a function of training systems have not been published for apple to date, similar studies in peach (Giuliani *et al.*, 1998) have reported an increase in photosynthesis in response to increasing levels of light intercepted (and have also pointed out that differences may exist among training systems). It is likely that similar results would be obtained for apple, lending supporting evidence to the reports of greater productivity for those systems, such as the Y-trellis, that are capable of maximizing seasonal light interception (Robinson and Lakso, 1991; Robinson *et al.*, 1991).

Studies relating crop load and gas exchange at the tree level have initially shown a somewhat loose relationship between the number of fruit per tree and

total tree NCE (Giuliani *et al.*, 1997a; Wünsche and Palmer, 1997b). However, when NCE was expressed in terms of tree leaf area, both studies showed greater specific rates for fruiting than for non-fruiting trees. This has been confirmed in a more recent study (Wünsche *et al.*, 2000). Removal of fruit early in the season probably causes a shift of resources towards greater vegetative growth, resulting in higher tree leaf area. This in turn may induce a greater capacity for light interception and thus lead to the higher observed NCE rates. In contrast, fruiting trees develop less leaf area, and they may thus show reduced light interception while maintaining high specific NCE rates, presumably driven by the carbon demand of growing fruit. So fruiting may not alter total tree NCE, because this appears to be a function of light intercepted, but it does stimulate the photosynthetic process, making the foliage more efficient. This has been confirmed by chlorophyll fluorescence studies, which have reported a decrease in photochemical efficiency for the leaves of trees that had been partially or totally defruited and, as a response to this, showed a reduced NCE per unit leaf area (Wünsche *et al.*, 2000).

9.4 Source–Sink Relationships

The importance of different leaf types for supporting fruit growth has been widely illustrated. Hansen (1971) demonstrated the dependence of fruit growth on current photosynthates, derived by spur and shoot leaves. Ferree and Palmer (1982) reported an important influence of spur leaves on fruit size at harvest and on fruit calcium concentration. Rom and Ferree (1984) reported a strong correlation between spur leaf area and cumulative yields over 17 years for nine apple cultivars. It is important to stress that this terminology refers to the primary spur leaves, which emerge prior to the flower cluster and form a whorl of very efficient, although limited, leaf area, which is capable of supporting the earliest stages of fruit growth, partitioning a significant amount of carbohydrates to the growing fruitlets.

The partitioning of carbon to different sinks (vegetative vs. reproductive) in the tree is under complex control mechanisms (including the influence of hormones, nutrients and water), but light levels can also influence the directions of these flows. Early in the season, when fruit set occurs, and soon thereafter during cell division, fruitlets receive photosynthetic carbon from primary spur leaves, which are the only carbon source for the fruit until the developing shoots attain sufficient leaf area to become net exporters – which occurs when there are around 13–15 unfolded leaves. Modelling work by Johnson and Lakso (1986), subsequently confirmed by radio-tracer studies (Corelli Grappadelli *et al.*, 1994), showed the effect of light levels on the time necessary for the transition of a shoot from being a net importer to being a net exporter. Shoots under high light levels would require comparatively less carbon (thus reducing their competitive demand) and would become exporters sooner in the season than shoots growing in low light conditions. Short shoots (2 cm long) would begin exporting photosynthates sooner than long shoots (50 cm) and contribute more carbon to the growing fruit in the early part of the season, when the potential for final fruit size is set (Lakso *et al.*, 1989). The validation of the model revealed

that heavy shade (70%) can delay by up to 2 weeks the transition of shoots from importing to exporting.

Reduction in fruit growth rates early in the season has been correlated with subsequent fruit drop (Zucconi, 1981). Among other physiological reasons that may bring about this reduction in growth rates, shortage of carbon supplied to the fruit has been proposed as a causal agent, prior and up to June drop (Schneider, 1977, 1978). Work with photosynthetic inhibitors (such as Terbacyl) or with neutral-density shade cloth (Byers *et al.*, 1985) supports this hypothesis: inhibition of photosynthesis up to 5 weeks AFB can lead to extensive fruit drop, whereas shading at later stages does not alter crop loads (Byers *et al.*, 1991) or fruit growth (Fig. 9.4).

Because the whorl of primary spur leaves is the earliest supplier of carbon to the fruitlets, it follows that these leaves are very important in supporting the initial growth of fruit during cytokinesis, when cell divi-

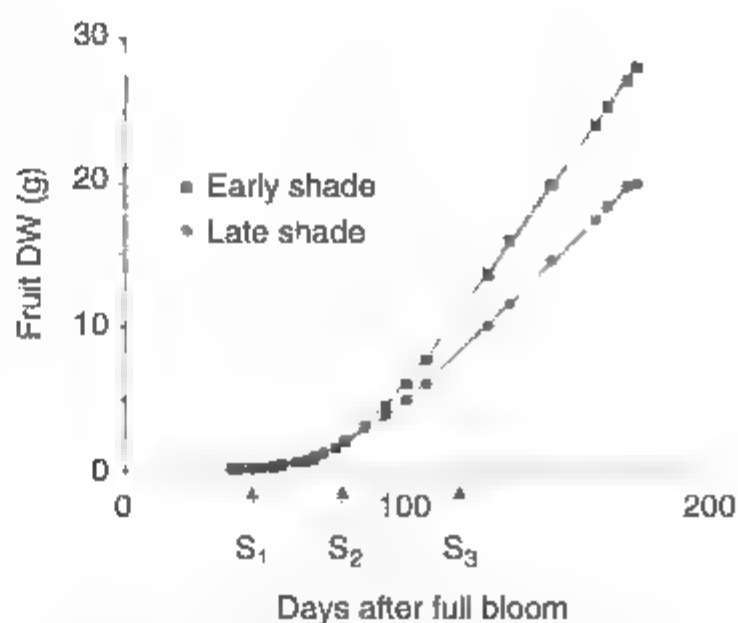


Fig. 9.4. Dry weight (DW) accumulation of 'Golden Delicious'/M.27 fruit grown on trees that were subjected to 7 days' shading with 70% neutral-density shading cloth, at different times after full bloom. Each symbol represents the average of at least 40 fruits, while the lines represent the fit of the expol near model to the actual data. One week of shading at 5 weeks after full bloom (S_1) caused extensive fruit drop, resulting in increased growth of the remaining fruit (early shade). Subjecting adjacent trees to two similar periods of shade at later stages (S_2 and S_3) did not cause any fruit abscission or any change in growth rate (late shade).

sion sets the potential for subsequent fruit development. This probably explains the good relationship that is normally found between the spur-leaf area and yield, where normally such relationships are not as good for the long-shoot canopy (Fig. 9.5, Sansavini and Corelli Grappadelli, 1992, Wünsche *et al.*, 1996). The light levels available to these leaves thus become very important, as shade can delay the onset of

carbon export or reduce the flux of that export. Studies that related the partitioning of light interception between primary spur and bourse-shoot leaves in the early season have concluded that an advantage exists for those canopies that maximize the amount of spur-leaf area that is well illuminated early in the season.

9.5 The Basis of Orchard Productivity

Theoretically, light interception sets the maximum potential for yield, as the latter cannot exceed the former. From the standpoint of light alone (but without ignoring the many other factors that have an effect on yield), the basis of orchard productivity lies within the complex relationships between orchard design components (such as tree form, tree spacing and row orientation) and sun position. These relationships affect the two essential properties required of a canopy: concurrent capacity for high light interception and good distribution throughout the canopy. Since training-system studies are expensive and time-consuming and do not yield useful data before several seasons have elapsed, modelling work has been instrumental in studying these relationships. It is appropriate therefore to start this section with a brief overview of modelling work and its influences on the evolution towards the increased planting densities that are used in modern training systems and orchard configurations worldwide

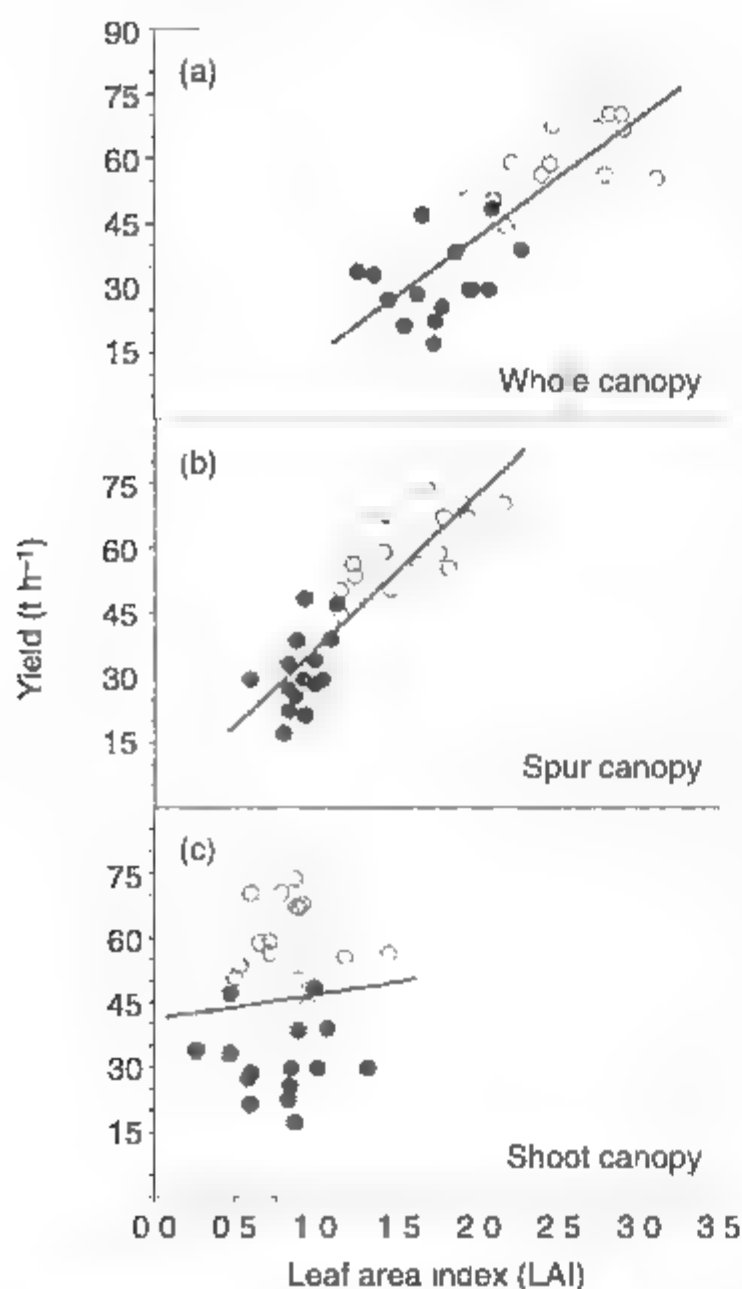


Fig. 9.5. The relationship between fruit yield (t ha^{-1}) and mean whole-canopy, spur-canopy and extension-shoot-canopy LAI (average for 3–5 and 10–12 weeks AFB) in a 4-year-old 'Jonagold'/'Mark 9' (●) and a 15-year-old 'Marshall McIntosh'/'M.9' (○) slender-spindle apple-production system in 1992. Linear regression equations ($n = 30$) are: (a) yield = $-12.74 + 27.37$ (total LAI), $r^2 = 0.656$; $P \leq 0.0001$; (b) yield = $-1.29 + 35.63$ (spur LAI), $r^2 = 0.774$; $P \leq 0.0001$; (c) yield = $-41.12 + 5.75$ (shoot LAI), $r^2 = 0.008$; $P \leq 0.643$ (From Wünsche *et al.*, 1996, reproduced with permission)

9.5.1 Models

Earlier models defined trees as solid, non-transmitting and non-reflecting canopies (Cain, 1972; Jackson and Palmer, 1972). They were mostly concerned with the overall effect of tree dimensions and spacings and row orientation on light interception. This work confirmed that the preferred row orientation should be N–S, in spite of the fact that, depending on latitude (which affects the elevation of the sun) and canopy height, this orientation does not always maximize the amount of light intercepted

by a canopy. However, much more uniform illumination of the canopy occurs in N S rows, independently of latitude and time of the year.

Recent studies with whole-tree chambers on slender spindle-trained trees on N S rows have revealed, however, that the diurnal gas exchanges of a tree have a complex relationship with light and temperature (Fig. 9.3), since photosynthesis normally peaks in the morning hours and tapers off in the afternoon, even if the amounts of light intercepted remain high, while the loss of water via transpiration often follows the vapour-pressure deficit (VPD) gradient, which normally reaches a maximum in the afternoon, closely following the daily temperature course (Giuliani *et al.*, 1997b). As a result, water-use efficiency (WUE) may be quite different at different times of the day. If further work should confirm the asymmetry of the gas exchanges around solar noon, this might pose the question of canopy orientation under an interesting new 'light'.

Since trees do not have solid, non-transmitting canopies, further refinements of these models took into consideration the transmitting capacity of the canopy. These refinements recognized the need to ensure that there are appropriate light levels throughout the canopy in order to maintain essential vital processes, such as flower-bud differentiation, ensure the high photosynthetic potential of the leaves, improve the tree's carbon balance and positively affect fruit quality traits, such as skin colour, soluble-solids concentration and firmness (Plate 9.2). Jackson and Palmer (1980) proposed simplified equations that accounted for the discontinuity in orchard canopies. They divided incoming radiation into two components: one representing the light that is directly transmitted to the orchard floor without interacting with the foliage (T_p); and one equal to that which would be intercepted by the canopy if it were non-transmitting ($F_{\max}$), minus a factor accounting for transmission through the canopy (T_c). The latter is a function of planting density, tree form and canopy density. According to this model, planting additional trees with optimal leaf density

(i.e. of unchanged T_c) is a preferable strategy, in order to increase light interception (thus reducing T_p) without increasing poorly illuminated fractions of the canopy, as would be the case if the leaf density of existing trees were increased by an equivalent amount of leaf area (Fig. 9.6)

The modelling work outlining the basis of orchard productivity, in terms of light interception and utilization, has also been useful in several instances of further modelling work, as is the case in work aiming to estimate the daily carbon gain of an apple tree (Lakso, 1992). More recent work with whole-tree chambers is leading the way towards new developments in modelling: results are confirming that photosynthesis at the whole-canopy level can generally be considered a linear function of instantaneous light interception. Subsequently, simple and accurate methods to determine the amount of light intercepted have been developed, which yield data that allow the tracing of contour maps of light/shade levels on the ground under a tree (Giuliani *et al.*, 2000) at different times during the day. From this information it is possible to derive a three-dimensional representation of the canopy, including an estimate of the leaf area exposed perpendicularly to the sun (which is more closely related to transpirational losses). It appears as though a reverse course might be possible where, by measuring the amount of light intercepted, the physical characteristics of the canopy may be able to be reproduced and these may then be used to estimate the tree's gas exchanges (E. Magnanini, Bologna, 2000, personal communication). If the slope coefficients for the linear relation between photosynthesis and light interception should prove to be fairly constant (a likely hypothesis under comparable tree conditions), whole-tree photosynthesis might be accurately estimated quite simply by measuring/modelling the light interception of a canopy. Preliminary indications, from studies including kiwi fruit, apple, peach, grape and pear whole-canopy gas exchanges (E. Magnanini and L. Corelli Grappadelli, Bologna, 2000, unpublished results), seem to be in good agreement with the above assumption

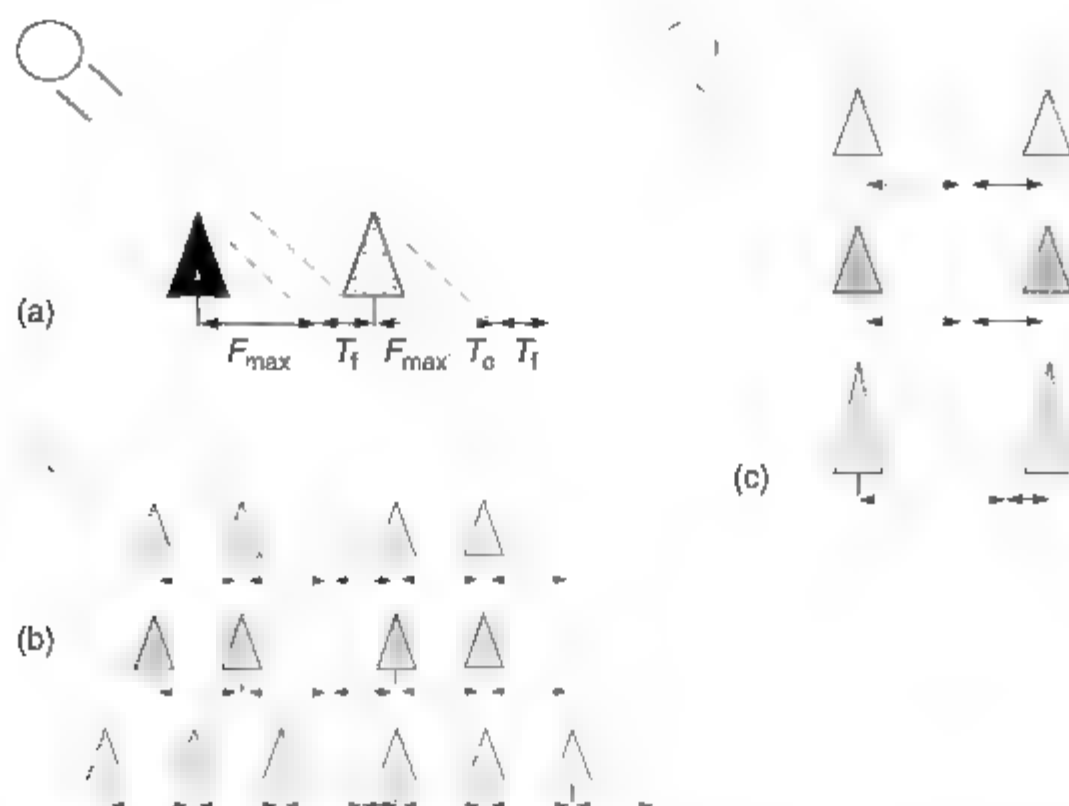


Fig. 9.6. Basic concepts in light interception. (a) The theoretical maximum light interception of a solid, non-transmitting canopy (F_{max}) is reduced, in real-life orchards, by two components: T_f , the fraction of light that misses the tree completely and is transmitted directly to the orchard floor, and T_o , the fraction of light that is transmitted through the canopy. The former is a function of tree shape, size and spacings, the latter is a function of the extinction properties of the foliage and the density of the canopy: the hatching reflects the degree of shade. (b) Increasing light interception in multi-row beds via increased foliage density might result in excessive shading of the inner canopy, while adding a row of trees without increasing canopy density would be preferable. (c) In single-row layouts, increasing the height (but within limits dictated by the distance between rows) will provide a similar increase in interception, without the inner canopy shading caused by increased canopy density. (Adapted from Jackson and Middleton, 1988)

9.5.2 Orchard configuration studies

Models have favoured orchard systems that are characterized by narrow (or shallow) canopies, as is the case with slender spindle, palmette (and in many hedgerow-forming systems), Y-trellis and the so called 'bed systems' of short (< 2 m) trees planted very close together, because they can combine high light interception with very good distribution of light inside the canopy. Experimental evidence has confirmed that very different orchard designs, based on varying tree forms, may achieve similar yield efficiency if these constraints are satisfied. Sansavini and Corelli Grappadelli (1992) demonstrated the efficiency of narrow canopies compared with tree forms that allowed the trees to grow dense and poorly illuminated canopies. They reported, across a range of tree densities, training systems and orchard configurations (from single to

multiple rows to bed systems), similar cumulative yields per hectare from the fourth to the seventh leaf. However, rather large differences existed when cumulative yields were expressed in terms of cumulative leaf area (Table 9.2). Despite different rootstocks (M.9 vs. M.27), a fivefold increase in planting density (1800 vs. 9000 trees ha⁻¹) and widely different orchard layouts (single vs. multiple rows), the bed systems and the palmette form exhibited similar efficiency (tonnes of fruit per leaf area) and both were 35–45% more efficient than the other systems tested, which were based on the slender spindle (or derived forms) in single or multiple rows. These systems had poorer light distribution profiles throughout their canopies than the more efficient ones (Corelli Grappadelli and Sansavini, 1989); this difference was attributable to rootstock/training system/density combinations that were not suited to the fairly vigorous environmental conditions

Table 9.2. Leaf area per tree divided between spur and shoot components and total, leaf area index (LAI), yield per hectare and fruiting efficiency (ratio of yield to LAI) for 'Golden Delicious' trees trained to different tree shapes, orchard designs and densities. Leaf area, LAI and yield data are cumulative figures from the fourth to the seventh leaf (Adapted from Sansavini and Corelli Grappadelli, 1992)

Training system	Orchard layout (no. of rows)	Planting density (trees ha ⁻¹)	Leaf area per tree (m ²)			LAI (a)	Yield (t ha ⁻¹) (b)	Fruiting efficiency (t ha ⁻¹ leaves) (b/a)
			Spur	Shoot	Total			
Slender spindle ¹	1	2667	6.4 c ²	40.0 b	46.4 b	12.4 b	243.2 a	19.6
Slender spindle ¹	2	2667	6.4 c	39.7 b	46.1 b	12.3 b	218.2 a	17.7
North Holland spindle ¹	3	3571	5.1 b	36.0 b	41.1 b	14.7 c	253.9 a	17.3
Mini spindle ³	6	8889	3.0 a	7.3 a	10.3 a	9.2 a	285.0 a	31.0
Mini bush ³	6	8889	3.0 a	7.2 a	10.2 a	9.1 a	279.4 a	30.7
Palmette ¹	1	1802	8.7 d	36.3 b	45.0 b	8.1 a	227.6 a	28.1

¹Rootstock: M.9

²Mean separation within columns by SNK test; $P = 0.05$.

³Rootstock: M.27.

experienced in the southern Po Valley of Italy. Similar differences in total yield and yield efficiency in favour of systems with better light interception/distribution profiles have been reported by other authors, comparing pyramid-type canopies either with slender spindle and trellis systems (Ferree, 1989) or with the Y-trellis (Robinson and Lakso, 1991; Robinson *et al.*, 1991).

All these studies illustrate the importance of high light interception that was derived by modelling work. Thus, the practical consequences of this work have been many. It has provided fundamental grounding evidence for the shift towards increased planting densities, by demonstrating the advantage of high-density plantings of low-vigour trees in terms of higher light interception early in the orchard's life, which resulted in earlier and higher initial bearing of the trees. This, combined with the multiplying factor of tree density, made possible greater initial yields (up to 10 t marketable apples ha⁻¹ in the second leaf (Sansavini *et al.*, 1989)). Additionally, it demonstrated the advantage of smaller trees, more closely spaced, in terms of light distribution within the canopy (Jackson and Middleton, 1988), and provided once again theoretical scientific grounds in support of the establishment of very high-density orchards, such as those reaching 6000–8000 trees ha⁻¹ (or even higher) currently (Sansavini and Corelli Grappadelli, 1997). One aspect suggested by models that subsequent work has not confirmed is related to the advantage of growing multiple-row beds of trees, which, contrary to the indications from modelling work, have not been performing in actual trials as might be expected. Many reports agree on the single-row layout as the most suitable for combining high productivity of high-quality apples with ease of management (multiple-row beds would require tailor-made and probably expensive equipment). The major drawback of these multiple-row plots has invariably been related to reduced light levels within the collective canopy formed by many adjacent trees, coupled with difficulties in management. As a result, today's very high-density

commercial orchards (sometimes in excess of 10,000 trees ha⁻¹) are all based on single-row layouts, with extreme reductions in the distance of the trees along the row (< 50 cm). These orchards represent extreme configurations, requiring highly skilled, extremely careful and timely management.

9.5.3 Light distribution

The interception of high proportions of the available PPF does not in itself guarantee the production of large amounts of high-quality apples per hectare. An even more important requirement is that the light be uniformly distributed to all or most parts of the canopy. This is because all factors influencing productivity are in turn influenced by reduced light levels. The issue is then one of optimizing the distribution of light within the canopy

9.5.3.1 Orchard design

From a theoretical approach, for a given planting density, the amount of light intercepted decreases with increasing 'rectangularity' of planting (in orchard design, rectangularity of planting is defined as the ratio of the spacing of trees between rows to their spacing along the row). However, the light distribution within the canopy may also be negatively affected by rectangularity. Working with orchard layouts designed to test these hypotheses, Wagenmakers and Callesen (1995) have reported that seasonal interception increases with decreasing rectangularity for a given planting density. They also demonstrated that more uniform light transmission to the orchard floor was achieved at the highest density, with a 1:1 rectangularity (i.e. with trees equally spaced between rows and along each row). However, practical considerations in general prevent the utilization of such a rectangularity ratio, since a minimum alley width must be maintained in order to allow room for mechanical equipment to move through the orchard – this is one of the main reasons against the adoption of the so-called 'bed systems' of planting.

9.5.3.2 Training systems

Based on the light-extinction characteristics of apple leaves, modelling work (Jackson and Palmer, 1980) indicates that, when leaf-area density in the outer parts of a canopy is increased (such as is often the case with large, vigorously growing trees), this causes an exponential decrease in the amount of light transmitted throughout the canopy. This explains the very strong decrease in light levels reported by many authors that have measured this parameter at different positions within a tree and across different tree shapes (Jacyna, 1978; Tustin *et al.*, 1988; Barritt *et al.*, 1991).

Since most of the plant's characteristics that influence the quality of production and the overall productivity of a tree are related to light levels, it is not surprising that a great deal of effort has been put into detailing the light profiles of training systems, as well as into making some of them more efficient by targeted pruning strategies. Medium- or long-term studies of training systems have, in general, reported similar yields of comparable-quality fruit from widely different training systems (Ferree, 1989; Palmer *et al.*, 1989; Sansavini *et al.*, 1989; Sansavini and Corelli Grappadelli, 1992), provided they were capable of comparable, high, light interception. In general, however, these studies have reported that fruit-quality attributes were more influenced than yield by light levels within the canopy.

In addition, the type of prevailing weather can have an impact on the light levels within a canopy: under climates typical of the northern European countries or the continental climate in the north-eastern USA, which tend to have a fairly high diffuse radiation component during the summer (for example, due to haze or light cloud cover), maximum light penetration to the interior canopy occurs under a mix of direct and diffuse radiation, rather than under maximum direct light conditions (Lakso and Musselman, 1976). As a result, some of the correlations that have been reported between light levels and fruit-quality parameters may not be as close as expected if they are studied under climates with different direct-diffuse

radiation ratios (this can be the case, for example, when comparing data from the very clear, high direct radiation environment of Washington State with those from the mid-Atlantic states (e.g. Campbell and Marini, 1992)).

9.5.3.3 Pruning

Pruning is a very important tool for guiding and controlling the growth of the tree in order to maximize orchard productivity. The goal of pruning when the tree is young, in the 'training' stage, is to attain the desired canopy form and size in the shortest possible time; following this, the tree enters the mature stage and pruning goals become different. In the young tree, the best approach to maximizing light interception is often to allow the plant to grow freely, without extensive removal of shoots and limbs (except for those systems like the Y-trellis or the palmette hedgerow that require branch selection and positioning). In young trees, light distribution is normally not a concern because the tree is 'open' to light penetration, and retaining a large amount of wood may reduce the total growth of the tree (which is beneficial in high-density plantings), both via an increased number of fruits and because of a lack of growth-promoting cuts. Often in this phase of orchard life, summer pruning is preferred because it is better suited to 'guiding' the tree into the desired development without leading to excessive regrowth (noting, however, that the timing and severity of summer pruning are critical). When a tree reaches maturity, after it has filled its allotted space, the challenge becomes that of maintaining flower bud differentiation throughout the canopy, as this forms the basis of tree productivity. The main goals of pruning a mature tree include preventing the canopy from exceeding its allotted space (to avoid shading neighbouring trees) and, above all, maintaining good light penetration through the vegetative volume, particularly for those cultivars that differentiate on 2- or 3-year-old wood, where it becomes essential to provide adequate light levels to maintain reproductive development. In most modern training systems,

which try to combine low cost with high efficiency and ease of management, the pruning strategies of standard-type mature trees almost always rely on branch removal (i.e. 'opening up' the canopy), rather than using selective thinning cuts on existing branches, in order to improve light penetration.

9.6 Light Effects on Physiological Parameters

Low PPFs in the visible range have been correlated with a number of negative effects in apple. These include poor flower-bud differentiation, reduced fruit set and shade leaf photosynthetic characteristics (such as reduced leaf-area density, nitrogen content and thickness). Fruit characters that are negatively affected by shade include fruit size, fruit colour, soluble-solids concentration and firmness. Also the content of mineral elements, such as calcium, and, to a lesser extent, potassium, phosphorus and magnesium, in the fruit is negatively influenced by the lack of light. The physiological mechanisms behind most of these responses are not fully elucidated, and the conclusion should not be drawn from the present discussion that light is the only regulatory factor involved, discounting other very important aspects, such as the influence of hormones and the roles of mineral nutrition and water relations. What can probably be stated is that light and its associated parameter, temperature, are the critical environmental factors that trigger adaptive tree responses. The mechanisms by which these adaptive responses are controlled and brought about are certainly many and likely to overlap in their potential influence. This discussion will centre only on the knowledge relative to light effects, since this is the scope of the present chapter.

As light interacts with the canopy, it undergoes both qualitative and quantitative changes, resulting in greatly diminished intensities and in a change in the red:far-red ratio towards longer wavelengths (Baldini and Rossi, 1987), which can trigger phytochrome-mediated photomorphogenesis. Most of the light-dependent responses

that have been observed in apple, however, are not related to (or are not strictly controlled by) phytochrome-mediated mechanisms. This has been demonstrated in several studies with neutral-density shade cloth, which reduces the intensity of light without altering the spectral composition of the radiation. This is not to say, however, that none of the phenomena influenced by light are insensitive to the relative composition of the spectrum.

9.6.1 Responses to light quality

9.6.1.1 Fruit colour

When fruit mature, their skin undergoes colour formation. This is a complex phenomenon, in which, among other processes, pigment synthesis (anthocyanins, carotenoids and flavonoids) must occur, along with chlorophyll degradation. It has been shown in red-fruited cultivars that anthocyanin synthesis is under the control of UV-B (< 320 nm) radiation, with a peak at 312 nm, and that this process can be partly stimulated by addition of radiation in the red region (Arakawa *et al.*, 1985). This effect is synergistic: it causes an increase in anthocyanin synthesis that exceeds the summation of that of the two wavelengths taken alone. Recent work with 'Fuji' trees subjected to treatments with light-reflecting mulches (Plate 9.3) (Ju *et al.*, 1999) has indicated increased activity of a light-inducible enzyme (uridine diphosphate (UDP)-galactose:flavonoid-3-*o*-glucosyl transferase (UGalT)) involved in anthocyanin synthesis (Ju *et al.*, 1995). The effect was greater for those mulches with a greater percentage of UV and IR reflectivity. The above explains the advantage for fruit-colour formation that is normally found in apples grown in alpine regions (South Tyrol in Italy) or under very clear skies in environments (such as Washington State and New Zealand) where the proportion of UV radiation is increased as a consequence of reduced absorption by the atmosphere, which preferentially absorbs more radiation in the shorter wavelengths (Nobel, 1983).

9.6.1.2 Fruiting

In cultivars that have low amounts of fruit set, fruit abscission has been reduced by additional lighting of trees at night with red-light flashes of variable duration (Greene *et al.*, 1986), an indication of the possible involvement of a phytochrome-mediated mechanism. In contrast, however, many studies have indicated that fruit abscission can be induced by neutral-density shading in the early part of the season. Fruit abscission is, therefore, another example of a physiological process where, very probably, more than one factor controls the responses observed.

9.6.2 Responses to light intensity

9.6.2.1 Flower-bud differentiation

Low light levels in the canopy result in reduced flower-bud differentiation. Despite the fact that this observation is reported in a number of studies, the reasons for this are not fully elucidated. As floral differentiation is a complex phenomenon, it should be expected that many factors are involved, including the role of hormones (a promotive role for cytokinins has been proposed, while gibberellins inhibit flower-bud differentiation). How light is involved in this process is still highly speculative. One hypothesis suggests that light might influence the direction of xylem sap flow (which contains cytokinins) via its effect on transpiration, but this hypothesis has not been conclusively confirmed by research work (Lakso, 1994). From a photosynthetic point of view, it is possible that reduced localized photosynthetic activity, due to low PPF, may negatively affect floral differentiation due to reduced carbohydrate fluxes. Some evidence exists that enhancing the carbohydrate status of the tree may enhance bloom in young trees (Hansen and Grauslund, 1980, cited in Lakso, 1994) or return bloom in heavily cropping trees (Lakso, 1994).

9.6.2.2 Fruiting

Fruit distribution within the canopy is highly correlated with light distribution, primarily because of the reduced number of flower

buds that are differentiated under low light, but also because of the lower fruiting potential of the spurs that develop under reduced light conditions. It is known that light levels below 15% of full sun result in very low or absent flowering and that optimum bloom occurs at light intensities above 50–60% of full sun. In addition, bloom in low light seldom results in adequate fruit set. As fruit set has been shown to depend on fruit growth rate, a direct involvement of carbon resources may be assumed, but other factors (see also Chapter 7) must be involved, for example, in determining the direction of carbon flows between different sources and different sinks (especially vegetative vs. reproductive sinks). However, it is known that not only do reduced light levels reduce the rates of photosynthesis, but they also alter the patterns of carbohydrate partitioning among leaves. Hence low photosynthesis and reduced hormone, nutrient and water supply may all lead to reduced fruit set in shaded regions of a canopy.

On young, developing bourse-shoot leaves, the morphogenetic responses to shade may occur within days of the imposition of shade (Table 9.1). Under natural conditions, therefore, these leaves may acquire shade leaf characteristics as, while they develop, the light levels naturally and progressively decrease as the canopy forms (normally maximum light interception is attained within 1 month after bloom). The primary spur leaves (which mature more rapidly than the bourse leaves) appear, in contrast, to be less influenced by the current light environment, but they may show the effects of the previous season's light levels under which the spur differentiated (Tustin *et al.*, 1992). This effect, coupled with that affecting the developing bourse-shoot leaves, might explain in terms of photosynthesis the reduced levels of fruit set in shaded parts of a canopy.

The duration of light periods has been shown to influence partitioning of carbon between different carbohydrate fractions (including sorbitol, sucrose, glucose, fructose and starch (Wang *et al.*, 1997)). The most relevant fraction is sorbitol, normally representing more than 50% of the total carbon fixed in

apple. Short light periods (2 h) favour partitioning of newly fixed carbon to sucrose (a more readily usable carbon form in the source leaf), whereas longer light periods favour partitioning of carbon into sorbitol. According to Wang *et al.* (1997), sorbitol might only be synthesized under longer light durations and so becomes an important fraction for export from the leaf (source leaves do not readily utilize sorbitol, as opposed to sucrose). An additional element supporting this hypothesis might be the fact that sorbitol synthesis requires nicotinamide adenine dinucleotide phosphate (NADPH) from the light reaction of photosynthesis, and this might be limiting under short light periods. If this hypothesis were confirmed, it might help explain reduced export from leaves that do not have sufficient light energy available for the synthesis of the export form of carbon, lending supporting evidence to the role of carbon shortages in shade to explain fruit abscission.

9.6.2.3 Fruit-quality traits

The knowledge that moderate to high light levels are necessary to ensure adequate productivity and fruit quality stems from the early determinations of light intensity, starting from the classic work of Heinicke (1966a,b) and Jackson (1967, 1968). Several authors subsequently reported 30% of available full sun as the minimum light level necessary to ensure good-quality fruit, as well as to maintain flower-bud differentiation (Cain, 1971; Lakso, 1980; Sansavini *et al.*, 1980).

The negative effects of diminished light levels within the canopy have been studied in depth. Jackson *et al.* (1977) provided a detailed analysis of the effects of shade on fruit-quality parameters, including post-storage assessment of physiological disorders that appear to be related to the light regime under which fruit develop. Further, they identified potential carry-over effects of shade from one season to the next, thus introducing an additional reason for careful management of the light environment within an apple tree. The concept of carry-over effects has been confirmed by other studies: given the natural tendency to alternate bearing of the apple tree, any cause that can

impair the vegetative-reproductive equilibrium of the canopy (such as weather, pruning, thinning, mineral nutrition and irrigation) can have profound effects. When a tree carries an excessive crop, the differentiation of flower buds is reduced and this can result in a lower crop the subsequent season, when intense vegetative growth can be expected. This vegetative flush, if uncontrolled, will result in reduced light levels, leading to the differentiation of poor-quality spurs. This can set in motion a series of shade-adapted responses that can result in loss of productivity and/or fruit quality. It is thus necessary to maintain high light levels throughout the canopy in order to avoid the onset of this behaviour.

Fruit from well-lit parts of the canopy tend to have a greater occurrence of some physiological disorders during storage, such as bitter pit and internal breakdown and rotting. Conversely, fruit from shaded parts of the canopy show increased transpiration and shrivelling during storage, which have been linked to a greater occurrence of cracks in the skin and with the more disorganized structure of the epidermal waxes on the shaded side of the fruit (Knuth and Stosser, 1987). Illuminated fruit (or the illuminated part of a fruit) show greater organization of the epidermal cells, with less cracking and better structure of the waxes, along with a higher fatty acids content, which has been related to an increased capacity to control transpiration and shrivelling by these fruit (Knuth *et al.*, 1987).

9.7 Controlling Light Levels in the Orchard

9.7.1 Bagging

Following the introduction of 'Fuji' in the early 1960s (Kikuchi *et al.*, 1997), the practice of growing fruit in bags during development ('bagging') has been adopted and perfected, in order to improve fruit coloration of this often poorly coloured cultivar (Plates 9.4 and 9.5). Individual fruits are placed within double-layered bags 4–6 weeks AFB. The bags are removed in two steps 4–5 weeks before the expected harvest date (Arakawa, 1998).

The outer bag, which provides the shading, is usually white or light-coloured, with the internal side coloured black. The inner bag is made of thinner, translucent paper, which can be of many different colours (red or green prevail), with the bottom open. The inner bag is removed a few days (up to 1 week) after the outer, and can contain waxes and fungicides to protect the fruit from bruising and diseases. In Japan, this technique has been extended to other cultivars, including 'Mutsu' (a non-red apple), and has been tested and adopted in several apple-growing areas of the world, with adjustments to adapt it to different light and temperature conditions (Fan and Mattheis, 1998).

Coloration of red apples is due to the synthesis of anthocyanins, which depends primarily on light intensity and quality (Arakawa *et al.*, 1985), temperature (Arakawa, 1991) and many other factors, as reviewed by Saure (1990). Along with the synthesis of anthocyanin, it is very important that chlorophyll degradation occurs, which also takes place during the final stages of fruit ripening. Reducing the amount of chlorophyll synthesized by placing the fruit within a non-transmitting bag may help in improving skin coloration at harvest provided the fruit is re-exposed before harvest in order to allow the light-dependent pigment synthesis to occur. Proctor and Loughheed (1976) reported decreased chlorophyll content and increased colour formation in apples that had been placed in aluminium bags from about 4 weeks AFB and exposed 20–30 days before harvest.

These observations and the underlying mechanism have been confirmed by other studies. Arakawa *et al.* (1985) showed the dependence of anthocyanin formation on UV-B (< 320 nm) light. They also indicated that different cultivars have different temperature optima for colour formation. Cultivars that do not colour well (e.g. 'Fuji') exhibit low temperature optima, between 15 and 20°C, and this condition needs to be coupled with high UV availability. The timing of bag removal is fairly critical for colour formation, as fruit seem to acquire and then lose the capacity for anthocyanin synthesis with time, as maturity approaches.

Apart from the effectiveness for colour formation, bagging has been reported to be capable of improving skin finish (Fan and Mattheis, 1998), reducing soluble-solids concentration and increasing the incidence of some postharvest disorders, including bitter pit (Witney *et al.*, 1991) and scald (Fan and Mattheis, 1998). Despite its positive effects, bagging individual fruit in the orchard is expensive and needs to be evaluated from an economic standpoint. Indications from Japan and the Pacific north-west region of the USA are that the use of bagging is declining because of cost, while, for the same reasons, it has never been adopted on a commercial basis in other important apple-growing areas (Italy, for example).

9.7.2 Reflectants

The knowledge that light can influence many vegetative and reproductive phenomena has led to investigations that have evaluated the possibility of increasing the light available in the lower and inner parts of the canopy through the use of reflecting materials (also termed reflective mulches). Such increases in light availability might have beneficial effects on tree performance. Most, but not all, of the materials tested include aluminium as a reflecting agent, coated or otherwise applied to different types of supporting material, including tar-paper, polypropylene, polyethylene or polyester films. White, non-metallized polypropylene film can also be used. The main conclusions from work with these materials include the following.

9.7.2.1 Light levels

Reflectants do improve the light levels in the lower, inner parts of the canopy (Doud and Ferree, 1980b; Mika, 1980), although their effectiveness decreases with the ageing of the material and it may also vary depending on the type of natural light environment. Mika (1980) reported a decrease of about 50% in reflectivity of aluminized tar-paper within 3 years of its deployment in the orchard. Doud and Ferree (1980b) reported a greater increase in light penetration within the canopy under

cloudy conditions than during sunny days. This may be related to a greater 'light-harvesting' capacity of some of the reflective materials under diffuse light conditions.

9.7.2.2 Fruit size and colour

An increase in fruit size in the lower canopy of apple trees was reported as a consequence of use of reflectants between 50 and 100 days before harvest (Moreshet *et al.*, 1975), contrary to the reports by Doud and Ferree (1980a), Mika (1980) and Ju *et al.* (1999). However, all these studies agree on increased apple skin colour in the fruit from the lower, inner parts of the canopy as compared with treatments where no reflective mulch had been used.

9.7.2.3 Physiological processes

While the early studies did not indicate any effects of the reflectants on photosynthesis or transpiration, a recent detailed study of the absorption of a tree under which a reflective ground cover had been applied (Green *et al.*, 1995), while confirming an increase in the light available inside the lower canopy and subsequent greater absorption of energy by the tree, also reported increased transpiration due to the greater radiation load on the leaves and coincident higher photosynthesis than from the same tree without a reflectant ground cover. These authors reported increases of 40% in total net all-wave radiation when the full alleyway was covered with the reflectant and this increase was accompanied by increased net photosynthesis (+34%) and transpiration (+26%).

More recently, with the widespread production of cultivars such as 'Gala' and 'Gala' strains or 'Fuji', reflectants have received renewed attention as a management tool to improve skin coloration. This approach is alternative to bagging, and it aims to reap the same benefits without incurring the high costs of that technique. In this case, the reflective mulch is applied 2-3 months before harvest (Andris *et al.*, 1998). Recent work (Ju *et al.*, 1999) has shown that materials with high reflectivity in the UV region can be quite effective in promoting red colour formation, via a stimulation of antho-

cyanin synthesis and of chlorophyll breakdown. They reported increased ethylene levels due to the reflectants, as well as increased activity of a key enzyme in the biosynthetic pathway of anthocyanin formation – UFGaT – an enzyme that is light-inducible. The increased anthocyanin synthesis recorded in parts of the trees with increased light because of the reflection might be due to a stimulatory effect of light on gene expression, with a possible involvement of ethylene in the regulation of such expression. This method too, however, requires careful economic evaluation, since its costs are not negligible, in particular those related to its disposal (the reflectants used normally remain in the field for more than one season, until they lose reflectivity or become too damaged to remain effective).

9.7.3 Shading to reduce sunburn

Apple fruit exposed to high light intensities during the growing season may develop sunburn damage, which is related to excessive temperatures in the fruit surface tissues. The intensity of damage can vary, but in all cases the commercial value of the fruit is lost or greatly reduced. Fruit temperature may vary between the exposed and the shaded fruit surfaces by more than 20°C, and the fruit reacts to this variation with the synthesis of heat-shock proteins, which impart protection from extreme temperature to these tissues. However, under very high light levels and warm, dry conditions, the extent of sunburn may be quite high. As a remedy, shading nets are used to cover the orchard. This is not only expensive, but may have negative effects on tree productivity (Widmer, 1997). Normally white (i.e. highly reflecting) nets are used, or evaporative cooling may be used for the same reason (however, this may also prove quite expensive where water availability is reduced). Recently, applications of white materials for coating the foliage and fruits have been proposed, based on kaolin clay particles, which aim to reflect the light. Experimental work is still under way for this latter technique, which, if viable, would have the advantage of low cost.

9.8 Conclusions

It can be concluded from this discussion that the first and foremost concern for the apple grower must be to ensure high levels of light interception in the orchard, coupled with homogeneous distribution of light throughout the tree canopy. This is achieved by N-S-orientated rows, with trees trained to forms that have a high area/volume ratio, i.e. which are thin and have a high proportion of the foliage exposed to the incoming radiation. The choice of training system, however, must be made keeping in mind the conditions that determine the growing potential of a site. For example, while it is possible to grow double- or triple-row beds under low-vigour conditions, such as occur in alpine environments, it would be impossible to adopt the same orchard design under vigorous conditions, such as those occurring in

the south-eastern Po Valley. Proper dormant and summer pruning strategies must be implemented to maintain the high levels of light penetration into a canopy. This is essential for flower bud formation throughout the canopy and to ensure that the buds are of high fruiting potential. Along with good flower formation and fruit set, high light levels inside the canopy also promote the formation of leaves with good photosynthetic potential and allow fruit to attain large size and good eating qualities. Recent developments that provide the possibility of physically manipulating light in the orchard (reflectants, shading nets, kaolin-based sprays) might be setting the scene for an array of new tools by which the growth and development of the trees may be manipulated, simply by affecting the most important environmental signal to which trees are sensitive: light

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10 Temperature

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Temperature has profound effects on all aspects of apple production. First, it sets boundaries on production areas. Being basically a temperate deciduous species, the cultivated apple needs a period of winter chill to break dormancy. Secondly, temperature controls the length of the growing season, which in turn limits the range of cultivars that can be grown in any one location. Thirdly, temperature alters the rate of development of all physiological processes, including key processes such as the rates of pollen tube growth, cell division and respiration. Fourthly, temperature alters the development of apple pests and diseases so that warmer areas frequently have more generations of pests than cooler ones.

10.1 Latitude

The genetic pool of the cultivated apple has resulted in a very adaptable species. Large-scale commercial apple production is generally limited to the latitude range of 25 to 52°. Apples can be grown outside this range if conditions are favourably warm in higher latitudes by virtue of being close to a water mass (e.g. Norway 60°N) or favourably cool in lower latitudes by virtue of elevation. Alternatively, at low latitudes the breaking of dormancy can be assisted by the use of specific chemical sprays, deleafing or the use of low-chill-requirement cultivars. Although apples can be grown in regions

where winter temperatures drop to -40°C , it is frequently in practice the rootstock that is killed by low temperatures rather than the scion cultivar

Temperature at a site is approximately determined by latitude. Charles-Edwards (1982) suggested, from a relatively small data set, that average mean temperature decreases by 0.45°C per degree of latitude from 10 to 55° , while the relative seasonal amplitude in temperature increases by 0.015°C per degree of latitude over the same range. Due to the large quantity of ocean in the southern hemisphere, temperatures for the same latitude tend to be somewhat cooler in the southern hemisphere than in the northern hemisphere. For example, mean maximum and minimum temperatures in Hawke's Bay, New Zealand, at $39^{\circ} 40'\text{S}$ are cooler than Davis, California, at a similar latitude of $38^{\circ} 32'\text{N}$ (Table 10.1). In contrast, when comparisons are made between temperatures in New Zealand and those in Japan at a similar latitude, New Zealand temperatures are cooler in the summer and warmer in the winter (Table 10.1). Although Aomori is at a similar latitude to California, the presence of the large land mass to the west of Japan results in considerably cooler winter temperatures than those that occur in Davis, where prevailing winds come off the Pacific Ocean and there is also a strong influence of the Sacramento River. The amelioration of climatic extremes when comparing sites with a maritime or continental climate at a similar latitude in the northern hemisphere is seen in Table 10.2, where East Malling, Kent (lat. $51^{\circ} 18'\text{N}$, long. $0^{\circ} 26'\text{E}$), is compared with Skierniewice, Poland (lat. $51^{\circ} 58'\text{N}$, long. $20^{\circ} 10'\text{E}$). The maritime environment of Kent does not experience the range of winter or summer temperatures experienced at Skierniewice. Even within a small area, there can be considerable changes in temperature due to altitude, slope and slope orientation and closeness to large bodies of water. In the extreme case of altering temperature with altitude, apples can be grown close to the equator at high elevations in countries such as Ecuador

10.2 Freeze Injury

Frost injury to flowers in the spring or freezing injury in the autumn or winter, which kills tissues or trees, accounts for greater crop losses than all other environmental stresses combined (Flore and Howell, 1987). It has also been estimated that the economic loss from freeze damage and cold injury to the USA's fruit industry exceeds the losses from insects, diseases, rodents and weeds combined (Larsen, 1970). Although several trends in cultivation have led to a reduction in the impact of winter freezes over the years – namely site selection, better management practices and the use of hardy cultivars and rootstocks – the ubiquitous and unpredictable nature of low-temperature cycles continues to cause extensive losses to the apple industry. Examples include the 1986/87 freeze in Poland, which killed over 13 million trees (25–30% of the total apple acreage), the devastating freeze of 1984/85 in western Europe (many millions of trees killed, actual numbers not determined) or the November 1955 and December 1964 freezes in the Pacific north-west of North America, which killed 2.5 million fruit-trees and injured 4 million trees in New York State, respectively. Although of less magnitude, it is common in the colder apple-growing regions for substantial tree-fruit losses to occur relatively frequently. For example, severe freezes that kill apple trees or lower yields occur every 5–7 years in eastern and western Canada (Coleman, 1992, Hall and Quamme, 1994).

Apple trees, like other hardwood trees, begin to harden in the autumn from the outer shoots down the trunk to the ground line, so injury is often observed on the trunks rather than on the shoot tips. Concurrently, not all tissues within the same genotype have the same hardiness (Cain and Anderson, 1976). Overall, fruit buds are more sensitive than shoots, and roots are more sensitive than shoots, with the cambial tissue being more sensitive than the xylem tissue. Under natural conditions, twigs can survive to -38°C but even the hardiest rootstocks can only survive to -18°C (Potapov, 1999). Although roots are consistently less hardy than stems, this is

Table 10.1. Comparison of mean minimum and maximum temperatures ($^{\circ}\text{C}$) at three sites at similar latitudes – Davis, California, USA, lat. $38^{\circ} 32' \text{N}$, long. $121^{\circ} 46' \text{E}$, Havelock North, New Zealand, lat. $39^{\circ} 40' \text{S}$, long. $176^{\circ} 53' \text{E}$, and Aomori, Japan, lat. $40^{\circ} 49' \text{N}$, long. $140^{\circ} 46' \text{E}$. (Temperatures for New Zealand have been reversed by 6 months to make comparisons between hemispheres easier.)

Location		Mean temp.	Jan	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sep	Oct	Nov.	Dec.
Davis, USA	Min.	7.8	2.3	4.1	5.3	6.7	9.5	12.3	12.9	12.6	11.5	8.7	5.1	2.5
Havelock North, New Zealand	Min.	7.0	1.8	3.2	4.8	6.5	8.4	10.7	12.0	12.0	10.3	7.2	4.4	2.1
Aomori, Japan	Min.	6.6	-3.9	-4.0	-1.4	3.8	8.8	13.8	17.8	19.7	14.9	8.2	2.8	-1.1
Davis, USA	Max.	23.0	11.5	15.5	17.9	21.8	26.6	31.0	33.7	33.0	30.5	25.6	17.3	11.6
Havelock North, New Zealand	Max.	18.8	13.4	14.3	16.4	18.7	20.7	22.2	23.9	23.8	22.2	19.6	16.6	14.1
Aomori, Japan	Max.	13.5	0.7	1.0	4.9	12.1	17.4	20.8	24.4	26.8	22.8	16.8	9.9	3.8

Table 10.2. Effect of maritime versus continental climate at two sites in northern Europe (East Malling, Kent, UK, lat. $51^{\circ} 18' \text{N}$, long. $0^{\circ} 26' \text{E}$, and Skierniewice, Poland, lat. $51^{\circ} 58' \text{N}$, long. $20^{\circ} 10' \text{E}$) on mean monthly maximum and minimum temperatures ($^{\circ}\text{C}$).

Location		Mean temp.	Jan	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sep	Oct.	Nov.	Dec.
East Malling, UK	Min.	5.6	0.8	0.8	2.1	4.0	6.5	9.5	11.6	11.3	9.4	6.3	3.4	1.8
Skierniewice, Poland	Min.	4.3	-4.4	-3.3	-1.2	3.3	8.0	11.3	12.9	12.5	9.2	5.0	0.6	-2.7
East Malling, UK	Max.	14.0	6.7	7.0	9.9	12.9	16.5	19.9	21.7	21.5	19.0	14.8	10.2	7.6
Skierniewice, Poland	Max.	12.6	1.2	2.4	6.2	13.0	19.2	21.8	23.7	25.2	18.3	12.8	5.4	1.9

closely associated with soil temperature, since stems below ground are no more resistant to cold than roots, and exposed roots can be as hardy as above-ground stems. There also exists evidence that rootstocks may impart hardiness to the trunks and that reciprocal effects also exist for the scion (Embree and McRae, 1991). Normally, apple production can extend into regions experiencing winter minimum temperatures in the range between -34 and -40°C because the low-temperature exotherm of apple xylem (-37 to -39°C) falls within this temperature range. When damage to the xylem occurs, it is as 'blackheart', a condition involving the darkening of the xylem. Repeated injury to the xylem weakens the tree, promotes the invasion of wood-rotting organisms and can lead eventually to death (Quamme *et al.*, 1982). However, even with 50% blackheart injury, it is possible for a tree to recover (Warmund *et al.*, 1996). Other visible symptoms of freezing injury include stem dieback, winter kill of dormant vegetative or flower buds, frost splitting of tree-trunks (also known as winter sun-scald or south-west injury), crown and root injury and soil-heaving damage. Freeze damage to shoot tips and vegetative and/or reproductive buds is common but affects mostly the current season's crop. South-west injury or splitting of the bark on the south-west side of the tree is also quite common in the northern hemisphere and occurs on cold days during the winter when the sun increases the temperature of the south-west side of the tree while it is frozen (Kesner and Hansen, 1976). Temperature differentials of $>16.7^{\circ}\text{C}$ can exist between the cambium on the south and north side of the trunk when ambient temperatures are below 0°C . When the elevated bark temperatures are followed by subsequent freezing, the cortical tissues are killed and the trunk cracks. Although serious, the tree usually recovers after 2–3 years if secondary pathogens have not further weakened the tree. Reflective paints and tree wraps applied to tree-trunks can help provide several degrees of protection for the tree and reduce or even eliminate south-west injury (Sakai, 1966). The most damaging freeze injury to the tree occurs when the crown and roots are affected, with the crown being the most critical to whole-

tree survival. Root-injured trees leaf out in the spring, but new growth and blooms are retarded and often wilt after hot weather. At this time, the scion often does not show signs of the oxidative browning that is typical of direct freezing. Root injury is often seen to occur in the upper soil levels, with the crown and roots below a critical soil depth often uninjured. Although most surviving roots that have vascular connections with the scion will probably produce new roots, even a small amount of root injury can reduce yields in subsequent years. None the less, an apple tree can lose a considerable amount of its root system and still survive if the crown remains healthy.

Freezing injury occurs in many forms and at different times of the year – it is not a single problem. Although most research has focused on midwinter hardiness, the acclimatization and deacclimatization characteristics of many cultivars and rootstocks may predispose them to injury from low temperatures in the autumn and early spring. The most important factor affecting the occurrence and severity of winter injury in Finland and in New Brunswick, Canada, was mild weather during midwinter followed by low temperatures (Kaukovirta and Syri, 1985; Coleman, 1992). Concurrently, the capacity of apple roots to retain cold-hardiness during intermittent short periods of warm weather, i.e. freeze-thaw cycling, is also very detrimental to survival (Privé *et al.*, 2001). Two freeze-thaw cycles at -3°C were as detrimental to root hardiness as one cycle at -9°C . Forsline (1983) also found that a 'so-called hardy' rootstock, 'Robusta 5', lost more than 6.7°C of hardiness after the first winter thaw. In response to all these different types of freezing injury, researchers have developed methods to identify the environmental variables most pernicious to production. For example, in the Okanagan valley of British Columbia, Canada, the main climatic factor associated with poor production the next year was the adverse impact of low temperature (-8.5°C) during late October and early November (Caprio and Quamme, 1999). This information helps breeders and growers alike to develop strategies best adapted for their region.

The basis for cold resistance is in the genetic constitution of the plant, so breeding is the preferred long-term approach to survival. This has been the central objective of numerous breeders across Canada, the northern USA, Sweden, Poland, northern China and Russia (Zagaja, 1994). *Malus baccata* L., *Malus prunifolia* Willd. and selections from *Malus sieversii* Ldb. were used to transfer the polygenic traits of acclimatization, cold tolerance and avoidance to their new selections (Korban, 1986). *M. baccata* L. was especially useful in the development of cold-hardy rootstocks (Stepanov, 1974). Half a century ago, the hardy cultivars available for marginal areas included 'Duchess of Oldenburg', 'Yellow Transparent', 'Wealthy', 'Charlamoff' and several 'Antonovka' types, all of relatively poor fruit quality but capable of surviving

severe winters. Through the efforts of breeders, new successful hardy introductions include 'Fantazia', 'Fireside', 'Haralson', 'Honeycrisp', 'Lobo', 'Katja', 'Mantel' and 'Northern Lights' (Zagaja, 1994). Winter-hardy rootstocks derived from northern breeding programmes include Alnarp 2, Bemali, the Budagovski series from Russia, Mark, Ottawa 3, the Kentville select clones from Canada and the P-series from Poland (Webster, 1999). Cold-hardiness screening is also being done for the fire-blight-tolerant rootstocks from the Cornell/Geneva breeding programme in the USA and the Vineland series from Canada (J.-P. Privé, personal communication). The lowest survival temperatures for some apple cultivars and rootstocks between November and February in British Columbia, Canada, are listed in Table 10.3, while general cold-

Table 10.3. The hardiness of 13 apple cultivars and seven rootstocks expressed as the lowest survival temperature (°C) (from Chilton *et al.*, 1994; Quamme *et al.*, 1999)

	Date			Mean
	November	December	February	
Cultivar				
'Mutsu'	-27.9	-32.9	-24.5	-28.5 a
'Jonagold'	-28.4	-31.2	-25.9	-28.5 a
'Golden Delicious'	-26.0	-33.0	-26.5	-28.5 a
'Gala'	-29.0	-35.6	-30.3	-31.6 b
'Sunrise'	-30.9	-35.8	-28.8	-31.8 b
'Elstar'	-31.4	-35.4	-28.3	-32.2 bc
'Granny Smith'	-31.7	-34.6	-30.8	-32.4 bc
'Red Rome'	-32.4	-35.7	-32.1	-33.4 bcd
'Braeburn'	-34.0	-35.7	-30.6	-33.5 bcd
'McIntosh'	-33.0	-37.2	-34.7	-35.0 cde
'Spartan'	-35.4	-37.6	-32.6	-35.2 de
'Fuji'	-35.9	-37.7	-33.8	-35.8 de
'Empire'	-36.1	-38.4	-35.9	-36.8 e
Mean	-31.8 a	-35.5 b	-30.6 c	
Rootstock				
M.7	-	-7.7	-7.2	7.5 a
M.9	-	-10.0	-9.2	9.6 b
A.2	-	-11.2	-11.2	11.2 c
J.9	-	-9.4	-12.3	11.8 c
B.9	-	-12.2	-12.5	12.3 cd
O.3	-	-12.0	-14.2	13.2 de
P.2	-	-12.6	-15.7	14.2 e
Mean	-	-11.0 a	-11.8 b	

Numbers in column and row followed by the same letter are not significantly different ($P = 0.05$) according to Duncan's multiple-range test.

hardiness classifications are provided in Tables 10.4 and 10.5. Besides their overall capacity to tolerate or avoid cold stress, there also exists some genetic variability in the ability to recover from a damaging cold event. The root system of certain rootstocks, such as Beautiful Arcade, B.118, B.490, and M.26, seem better adapted to recovery than M.9, M.7, MM.111 or O.3 (Privé and Embree, 1997). Interestingly, some rootstocks, such as O.3, have good mid-winter hardiness but poor recovery. This is

probably due to this rootstock's poor ability to regenerate new roots.

At extremely low temperatures, apple tissues have evolved mechanisms to either avoid or tolerate the ice formation within their tissues, which causes cell death. Generally, xylem tissues avoid freezing injury by freezing-point depression or deep supercooling, while bark and buds tolerate low temperatures by preventing intracellular ice formation (Quamme *et al.*, 1982; Kang

Table 10.4. Classification of the winter-hardiness of apple cultivars based on reported differential cold-hardiness after test winters and artificial freezing tests (from Forsline, 1983; Chilton *et al.*, 1994, Quamme *et al.*, 1999, Friedrich and Fischer, 2000; A. Czynczyk, personal communication)

Tender	Moderately tender	Hardy	Very hardy
'Cox's Orange Pippin'	'Braeburn'	'Alwa'	'Antonovka'
'Golden Delicious'	'Delikates'	'Cortland'	'Columbia'
'Gravenstein'	'Elstar'	'Empire'	'Dolgo'
'Jonagold'	'Gala'	'Fantazia'	'Haralson'
'Jonathan'	'Granny Smith'	'Fuji'	'Kerr'
'Melrose'	'Ligol'	'HoneyCrisp'	'Mantet'
'Mutsu (Crispin)'	'Northern Spy'	'James Grieve'	'Norland'
'Newtown'	'Red Boskoop'	'Jersey Mac'	'Rescue'
'Ontario'	'Red Delicious'	'Lobo'	'Wealthy'
'Sinta'	'Redkroft'	'Lode'	
	'Red Rome'	'McIntosh'	
	'Sawa'	'Melba'	
	'Sunrise'	'Northern Lights'	
		'Spartan'	
		'Vista Bella'	

Table 10.5. Classification of the winter-hardiness of apple rootstocks based on reported differential cold-hardiness after test winters and artificial freezing tests (from Privé and Embree, 1997; Potapov, 1999; Quamme *et al.*, 1999; Zhabrovsky and Samus, 1999; Friedrich and Fischer, 2000; A. Czynczyk, personal communication)

Very tender	Tender	Moderately hardy	Hardy	Very hardy
M.7	J-TE-D	B.118	Antonovka	Beautiful Arcade
<i>Malus halliana</i>	J-TE-E	B.490	Anarp2	<i>Malus baccata</i>
MM 104	J-TE-F	J.9	B.9	Columbia
	M.2	MAC 1	KSC 7	Robusta 5
	M.4	MM 106	KSC 14	
	M.9	MM 111	KSC 28	
	M.11	O.3	M.26	
	P.16	P.1	P.2	
		P.59	P.14	
		P.60	P.18	
		Supporter 4 (Pi-80)	P.22	
			YP	

et al., 1998). Tissues exhibiting deep supercooling can maintain supercooled cellular water to -38°C and involve freeze avoidance to the point of spontaneous nucleation of the cellular solutions (Burke *et al.*, 1976). It is this degree to which deep supercooling occurs that determines the higher latitude limits of apple production. However, under certain circumstances, certain cells can retain cellular water in a supercooled state to temperatures as low as -47°C . Lindén *et al.* (1996) reported LT_{50} of -46° and -43°C , respectively, for xylem tissue of the apple cultivars 'Antonovka' and 'Samo' grown in southern Finland. Interestingly, dehardening treatments at -14°C decreased this resistance by $12\text{--}15^{\circ}\text{C}$. Compounds that help tissues supercool and help prevent or minimize injury during freezing are known as cryoprotectants and include sugars, betaines, amino acids, polyols, oligosaccharides, antioxidants and antifreeze proteins, such as dehydrins (Kaye and Guy, 1995). In bark tissues and buds, ice first forms extracellularly, and then intracellular water migrates to the extracellular ice crystals due to the existing water-potential gradient (Sakai, 1965). Ice does not penetrate the cell membrane and therefore intracellular freezing is avoided. With proper treatment, buds from most apple cultivars can even survive exposure to liquid nitrogen temperatures of -196°C , and this is the preferred method for germplasm preservation (Tyler and Stushnoff, 1988). Sakai (1965), however, could not achieve survival of xylem ray parenchyma in liquid nitrogen. In both vegetative and floral buds of apple, the ice crystals are formed mostly in the scales and axis, but some crystals can also be found in the bud apices or flowers. This is unlike peach, which does not form ice crystals directly in the floral parts. Therefore, injury in peach occurs only from excessive dehydration rather than from freezing *per se* (Vertucci and Stushnoff, 1992). Although the amount of water in plant cells is negatively correlated to cold-hardiness, it is the fraction of unfrozen water within the cells that is important for survival (Bittenbender and Howell, 1975). Thus, it appears that the tolerance of apple buds to freezing injury

involves both an increase in tolerance to dehydration and an increase in the amount of unfreezable water (Kang *et al.*, 1998).

Freezing injury can occur even when tissues are fully hardened, because the dehydration/rehydration cycles involved in freezing have dramatic effects on both membranes and their cellular ultrastructure. The thermal stress placed on membranes during cooling can result in transitions from the liquid crystalline to the gel phase, which has important deleterious consequences. As a result of the transition, the cell may leak its contents to the surrounding medium, possibly due to defects in the bilayer between gel and liquid crystalline domains. In addition, the transition may lead to phase separation of membrane constituents in the plane of the membrane (Quinn, 1985). Seasonal ultrastructural changes are also involved in the changes in the physical and functional properties of cold-adapted apple cells. The ability of cells to adjust the balance of metabolites between vacuoles and the cytoplasm reversibly and to synthesize new components within the cytoplasm can influence the tissue's resistance or susceptibility to the stress-producing effects of the dehydration that occurs during freezing (Kuroda and Sagisaka, 1993).

Although breeding is the preferred approach to survival, this takes time, so cultural practices that help avoid or tolerate freezing injury are often used in marginal areas of production. Usually, any practice that helps maintain a healthy tree will be beneficial for survival, so tree condition is as important as its genetics. Cold acclimatization is an active process and requires energy and a carbon source, so it is not surprising that a certain minimum level of sugars or carbohydrates is necessary for the development of maximum winter-hardiness. Thus, it is also expected that shading, excess cropping, foliage damage, poor nutrition, very dry or wet soils and heavy pruning can reduce the trees' ability to tolerate freezing temperatures (Flore and Howell, 1987). Early natural defoliation is believed by growers to be an indicator of early acclimatization to winter damage, i.e. the earlier the leaf fall, the greater the acclimatization. This

view is supported by evidence that actively growing shoots are less hardy than those that have stopped growing. However, earlier leaf fall is not always associated with greater hardiness. Earlier leaf abscission results in fewer total carbohydrates being produced by the leaves, and this may reduce hardiness for trees that are low in vigour or for trees that have cropped heavily (Flore and Howell, 1987). Likewise, nutrition and fertilization play a role in cold tolerance, but it is most often overplayed. Generally, trees that are adequately supplied with nutrients are hardier than those that are undersupplied or have excessive nutrients available. Although the actual mode of action of nitrogen on cold-hardiness has not yet been determined, it is likely to be via carbohydrate accumulation. Recent studies suggest that postharvest foliar application of nitrogen can be beneficial to hardiness by the remobilization of this nitrogen (mostly from rubisco) out of the leaves and into the buds, wood and roots before leaf fall. This practice, however, may cause the leaves to remain physiologically active longer and might affect leaf fall, depending on location. Tree losses from root injury are often found on sandy or gravelly soils because these soils retain less moisture and consequently have reduced heat capacity. However, wet soils can have lower temperatures because of greater heat conductivity, so the best soils for reducing freezing injury are those where conductivity is low and heat capacity is high. Vegetative ground covers and/or mulches, combined with a trapped insulating blanket of snow, may be the most efficient and expedient means of preventing winter injury to the roots from low soil temperatures (Privé, 1994).

10.3 Dormancy

Other than on very young trees, vegetative growth of apples is complete after about 2–3 months, with the formation of terminal resting buds. Although these buds can be induced to grow again in the current season by defoliation, they lose this ability as the trees pass into autumn. This ability to start

growth following defoliation is used to prevent the tree entering dormancy in some areas of the subtropics, where there is inadequate chilling; in this context the trees will flower after defoliation and the trees can bear fruit twice each year. In temperate regions, however, the buds become dormant and will not begin growth until a period of winter chill is followed by warmer conditions in the following spring. This is a common occurrence among temperate tree species and enables the tree to withstand the cold conditions of winter. Winter dormancy is also known as rest, true dormancy or endodormancy (Lang, 1989). As temperature is the main environmental factor controlling dormancy, several attempts have been made to quantify the relationship between chilling and temperature. The earliest attempts were made based on the number of hours below 7°C. Most commonly used today is the non-linear temperature-response Utah model, where dormancy is satisfied by the accumulation of a set number of chilling hours (Anderson and Seeley, 1993), or one of a similar form described by Shaltout and Unrath (1983). In the latter model the temperature response is a parabolic one, with maximum chilling efficacy at 7.2°C and zero responses below -1.1°C and at 15°C.

Temperatures higher than 15°C produce an increasingly negative effect on chilling, i.e. a negation of previous chilling effects (Fig. 10.1). Cultivars vary widely in their chilling requirement, with, for example, 218 units required for 'Anna' through to 1516 units being required for 'Wright No. 1' (Hauagge and Cummins, 1991), although the majority of cultivars are in the 800–1200 range of chill units. This wide range of chilling requirements enables apples to be grown from the subtropics in Israel, Brazil and Mexico to higher latitudes such as Canada, Norway or Russia. The negation of winter chill by high temperatures is a particular problem in warmer climates, such as those that occur in Israel and South Africa. The model of Erez *et al.* (1990) was developed for these warmer conditions. Although warmer conditions can negate chilling, experimental work suggested that this was only a partial negation, as the negation depended upon

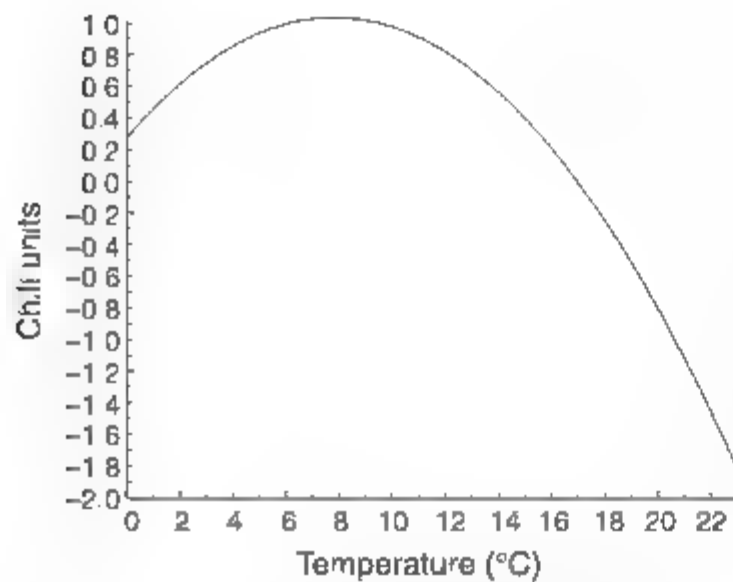


Fig. 10.1. Relationship between air temperature and chill units used by Hauagge and Cummins (1991) fitted to data from Sha tout and Unrath (1983).

the magnitude and the duration of the high temperature exposure. The model postulated a dormancy-breaking factor that was accumulated in buds in a two-stage process, the first step being the formation of a precursor, which was reversible, but, once a critical portion of the precursor had been accumulated, this was transformed into the stable dormancy-breaking factor. This second stage was not reversible.

The symptoms of inadequate chilling are seen in delayed and poor bud break, a prolonged flowering period, a low proportion of flowering spurs and poor lateral leaf-bud development. Apples are, however, grown successfully in areas that frequently do not receive adequate winter chilling (e.g. Israel, Brazil). In these areas the trees are treated to enhance bud break. A wide range of chemicals have been used for this purpose including mineral oil, dinitro-*ortho*-cresol (DNOC), hydrogen cyanamide, potassium nitrate and 6-benzylaminopurine (Lang, 1989).

Following the completion of dormancy, development is dependent on bud temperature, as altering spring soil temperature by warming or cooling to give conditions in the 18–26°C or 1–4.5°C range, respectively, compared with the control of 4–16°C, did not influence the time of anthesis of apple flowers (Hammond and Seeley, 1978). The development of flower buds has been correlated with the accumulation of growing degree-

hours (GDH) above a base temperature of 4.5°C (Hamer, 1980), so that about 290 GDH are required for full bloom of both 'Delicious' and 'Cox's Orange Pippin'. Hamer assumed a linear response to temperature above the base temperature. This assumption is frequently used in models based on thermal time, as is the assumption of a constant base temperature. Other workers, e.g. Winter (1986) and Anderson and Seeley (1993), have assumed a non-linear model and, although both of these models are approximately linear up to 20°C, this would encompass the temperatures experienced by Hamer in Kent. With the fluctuating temperatures during spring, the relationship between GDH and accumulated growth can be approximately linear, even if bud growth rate is not exactly linearly related to temperature (Cannell, 1989). It is important to understand that the first visible external signs of bud development occur after 30–40% of the GDH accumulation has taken place (Anderson and Seeley, 1993).

Bud temperature is only approximated by screen air temperature. Hamer (1986b) found that, with light winds and high solar radiation, buds could be up to 4.5°C above air temperature during the day, while Landsberg *et al.* (1974) showed that bud temperatures at night could be 1.5°C below air temperature under clear sky conditions. Care must therefore be exercised in extending detailed studies done by manipulating tissue temperatures under controlled conditions to the orchard environment, where screen air temperature may be the only estimate of temperature. In some studies, solar radiation has been included as an additional term in the relationship between bud development and growing degree-days (GDD) to account for this effect (Cannell, 1989).

10.4 Spring Frosts

Although, when fully dormant, apple trees can withstand –38°C, once dormancy is broken and active growth has begun, flowers are very sensitive to low temperatures and can be killed by late spring frosts. The critical temperature for damage to the tissues

decreases as the flower buds develop (Table 10.6), although some minor hardening is possible if the flowers have been exposed to low temperatures and dry conditions prior to the frost event. Within the apple flower, the styles and ovules are more sensitive to damage than the surrounding tissues. Following a damaging frost, brown damaged tissues can easily be seen by eye after sectioning the flower longitudinally with a razor-blade. Cell death results from intracellular ice formation causing mechanical damage and excessive dehydration (Modlibowska, 1975). Less severe damage to the flower can result in lopsided fruit, due to partial damage to some ovules. Frost rings and russet resulting from damage to the epidermal cells, which subsequently produce phellogen and cork formation, are also typical of non-lethal frost events. In some cases the skin splits due to ice formation beneath the skin of the flower receptacle, again resulting in russet development.

By far the most economical way of avoiding frost damage is to select sites that, due to location, slope and aspect, have a low risk of spring frosts, coupled with good cold-air drainage (see Chapter 11). There are, however, a number of physical steps that are used to reduce or eliminate late-spring frost damage, all of which rely on the supply of heat to the sensitive tissues. The flower tissues can be warmed using warm air from heaters (e.g. propane heaters or smudge pots) or by making use of warmer air above the trees (see Chapter 20). Generally under radiation frost conditions, there is a temperature inversion – air temperature near the ground is cooler than that several metres above the trees. So-called wind machines can be used to stir up the temperature-inversion layer and raise the temperature of the flower-buds. These machines, however, are limited to regions where there is a strong temperature inversion. An alternative approach is to use water

sprinkling, which takes advantage of the latent heat of freezing. In this case, as ice will not form within the tissue until its temperature drops below -2°C , the bud is prevented from reaching that temperature by the continual supply of water to the outside of the bud. As the water freezes, the latent heat of freezing is released to the bud and, assuming water continues to freeze, the bud does not drop to temperatures that will cause damage. The tree, however, becomes encased in a layer of ice. Although water sprinkling is a very effective means of frost protection, it does require an adequate supply of water, as the precipitation rates required are up to 2.5 mm h^{-1} to provide protection in an air frost of -4°C (Hamer, 1986a). Successful frost avoidance with water sprinkling therefore requires both an ample supply of water and free-draining soils.

The risk of spring frost injury can be further reduced by the use of late-flowering cultivars or by artificially delaying bloom. Water sprinkling has been used successfully to delay blossoming of apples (see Chapter 20). Bud temperatures can be reduced by the evaporative cooling of the water. The cooled bud therefore becomes like a wet-bulb thermometer, with the greatest cooling evident in dry environments, such as those in Utah, where this technique first came to prominence. Temperature differences of 20°C were observed between sprinkled and non-sprinkled apple buds in the middle of the afternoon in this dry environment, resulting in a bloom delay of 17 days (Anderson and Seeley, 1993). In the more humid environment of Kent, UK, Hamer (1986b) found a maximum difference of 9.2°C between unwetted and wetted buds. In Utah, calculations based on spring temperatures over a 45-year period suggested that a bloom delay of 20 days could have reduced annual crop losses from 33 to 7%, depending on the year. Bloom delay is fre-

Table 10.6. Critical temperatures ($^{\circ}\text{C}$) for developmental stages of apples

	Green tip	Tight cluster	Pink	Full bloom	Post bloom
Temperature for 10% kill	-7.8	-2.8	-2.2	-2.2	-2.2
Temperature for 90% kill	-12.0	-6.1	-4.1	-3.9	-3.9

quently accompanied by a delay in harvest, although the delay is commonly shorter than the delay in blossoming. Consequently, the technique may increase the risk of cold damage at harvest, and cultivars need to be chosen accordingly in short-season environments. In terms of timing, water sprinkling is best applied immediately after endodormancy has been completed and stopped at green tip (Anderson and Seeley, 1993). One of the drawbacks of the technique was highlighted by Hamer (1981), who found that, although water sprinkling delayed blossoming by 14 days in England, the watered buds had a higher moisture content and were consequently less hardy than unwatered trees at the same stage of development.

In contrast to the situation in regions of good winter chill, where water sprinkling may be used to delay flowering, in regions of inadequate chilling, water sprinkling during dormancy could enhance the accumulation of chilling hours and, if stopped at the end of endodormancy, could result in earlier flowering of apples.

10.5 Spring Temperatures

Even in the absence of frost injury, temperature over the blossoming period can have a dramatic effect on fruit set, which in turn can result in major changes in yield and fruit size. Most apple cultivars are self-incompatible, so conditions suitable for pollen transfer during flowering are necessary. The activity of the pollinators, chiefly insects, is enhanced under warm, dry and non-windy conditions. Even if pollen is successfully transferred between flowers of compatible cultivars, the rate of pollen tube growth is temperature-dependent. Under a mean daily temperature of 15°C, pollen tubes take 2 days to reach the ovules (Fig. 10.2), compared with 4 days at 13°C and 8 days at 9°C (Williams, 1970).

Some cultivars (e.g. 'Cox's Orange Pippin') are inherently weak in female fertility and are thus particularly prone to adverse weather conditions at flowering (Wilson and Williams, 1970). Modlibowska (1975) quotes a threefold higher yield for

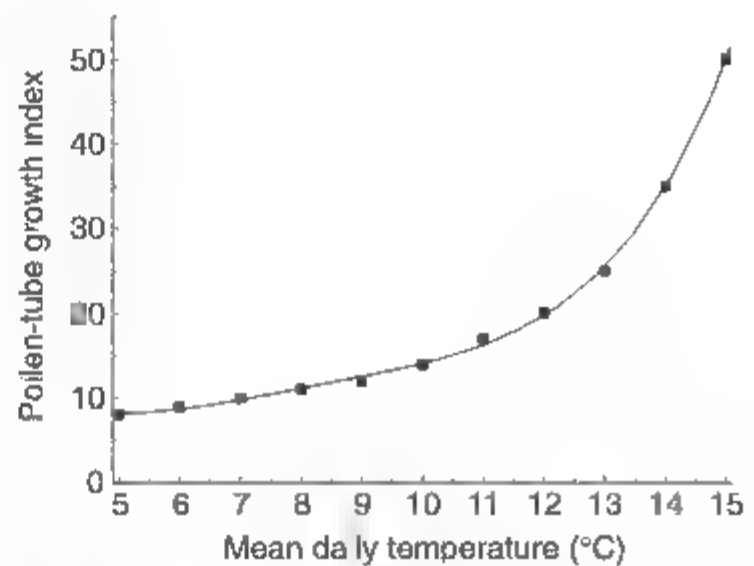


Fig. 10.2. Effect of daily mean air temperature on pollen-tube growth index for a 24-h period. Pollen-tube growth is completed when the index reaches 100. (Figure drawn from data in Williams, 1970.)

'Ellison's Orange' than for 'Cox's Orange Pippin', following a frost event that resulted in equal damage to the flowers.

In many fruit-growing areas, the set of flowers is such that the numbers of young fruitlets have to be reduced quite drastically to ensure market requirements of fruit size and quality and to achieve adequate return bloom the following year. Chemical thinners are frequently used but the efficacy of nearly all of these products is temperature-sensitive (see Chapter 16). Williams and Fallahi (1999) suggest that naphthaleneacetic acid (NAA) has a temperature optimum of 20–25°C, without the risk of overthinning, compared with 15–25°C for carbaryl and 20–25°C for ethephon, while Wertheim (2000) reported that the efficacy of the blossom burner ammonium thiosulphate (ATS) was much greater at 20°C than at 14°C. Due to the generally higher temperatures during application of NAA in the Pacific Northwest, the rates of chemical used can be half of those used in the cooler eastern states of the USA. The unpredictability of thinning efficacy still remains one of the major problems of chemical thinning, and Wertheim (2000) has recently suggested that more work is needed to elucidate the effect of weather factors, including temperature, and their interactions on the action of chemical flower and fruit thinners.

10.6 Length of Growing Season

The length of the frost-free period effectively determines the length of the growing season for apples in higher latitudes, as the first air frosts in the autumn lead to rapid defoliation of the trees; consequently there is a general trend of longer growing seasons at lower latitudes. Taking the data of Kronenberg (1988, 1989), a data set that does not include sites with a major continental influence, there is a reasonable effect of earlier flowering at lower latitudes in northern Europe (Fig. 10.3), with there being, for each degree lower latitude, an earlier blooming of 2.6 days. This is remarkably similar to the 2.5 days calculated by Wagenmakers (1991) with a different data set. There is, however, a wide range of cultivar requirements of days from flowering to picking. This can be as short as 90 days with 'Beauty of Bath' to 200 days for 'Granny Smith'. Consequently sites with long growing seasons have a wide range of cultivars available to them, whereas sites with short seasons are very limited in the cultivar choice (e.g. in Norway at 60°N the major cultivars are 'Aroma', 'Gravenstein' and 'Summerred').

The length of the period from flowering to harvest for one cultivar does show some variation from year to year. Luton and Hamer (1983) found that this period for 'Cox's Orange Pippin' could vary from 127

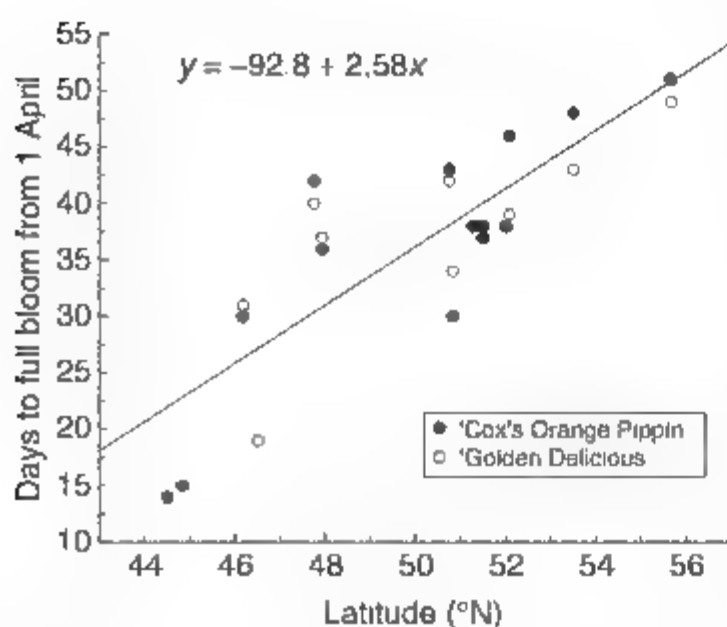


Fig. 10.3. Relationship between latitude and time of bloom for 'Cox's Orange Pippin' and 'Golden Delicious' derived from data in Kronenberg (1988, 1989).

to 153 days in Kent, UK, over a 22-year period. Although there was a general trend of an earlier bloom date resulting in a longer period of growth, there was also an additional effect of warm summer temperatures leading to a shortening of the developmental period. Each 1°C rise in mean temperature during June–August resulted in the harvest date being brought forward by 3.5 days.

10.7 Assimilation and Respiration

The temperature responses of leaf photosynthesis and respiration are very different. The leaf assimilation rate shows a parabolic response to temperature, with a peak at about 30°C, but with a broad shoulder in the 15–35°C range (Lakso, 1994). The leaf assimilation rate, however, drops off rapidly above 35°C. In contrast, leaf dark respiration shows an exponential increase in temperature, so that over the 10–30°C range, for each 10°C rise in temperature, the respiration rate increases by a factor of 2.5 (Lakso, 1994). The respiration rates of other tissues – wood, fruit and roots – also show an exponential increase with temperature, although the coefficients are somewhat different and vary with the time of year. The respiration rate is the sum of two parts, maintenance and growth respiration, where the former is associated with the energy required for protein turnover and the maintenance of ion gradients and the latter is the energy required for new tissue synthesis, which is essential for growth. It is maintenance respiration that is temperature-sensitive. Consequently, in warmer climates the cost of maintaining cell function increases. Lakso (1994) has drawn attention to the high yields obtained in New Zealand and explained these partly by the combination of high solar radiation, ensuring high rates of photosynthesis, coupled with relatively cool temperatures, ensuring low maintenance respiration. As an example of the effect of temperature on whole-canopy gas exchange, which is the balance between respiration and assimilation on the above-ground portion of the tree, Francesconi *et al.* (1997) found that CO₂ exchange of 4-year-old potted 'Royal Gala' trees decreased by 44%

when air temperature was increased from 18°C to 34°C, while it increased by 52% when the temperature was reduced from 18°C to 13°C. The authors acknowledge that there was a confounding of air temperature with vapour-pressure deficit but this does frequently occur in the field. Nevertheless, the results emphasize the very different response of the whole tree to temperature compared with that of the individual leaf

10.8 Fruit Growth

The seasonal pattern of apple fruit growth is defined by an initial 35–50-day period of exponential growth following fertilization, coinciding with rapidly increasing fruit cell number, followed by a more or less linear growth phase until harvest maturity, during which fruit size increases predominantly through cortical cell expansion. An examination of the influence of temperature on fruit growth and ripening among ten apple cultivars in four European locations led Kronenberg (1988) to propose three sensitive periods. Fruit development in the first month following flowering and in the period immediately preceding harvest responded positively to high temperatures. He concluded that the extended growth period between these two stages (probably the fruit cell-expansion phase) was insensitive to temperature

Fruit growth associated with cell division, immediately following bloom, appears to be very temperature-responsive and important in establishing seasonal fruit-size potential. In a comparison of fruit growth of four cultivars over two seasons, larger fruit size at 42 days after full bloom (DAFB) was associated with higher temperatures and an increased rate of cortical cell division (Bergh, 1990). However, higher temperatures also enhance fruit set, resulting in a higher fruit number per trunk cross-sectional area, which can confound the exploration of relationships between fruit size at 42 DAFB and size at harvest.

In controlled-environment studies, using methods that avoided crop competition effects, Warrington *et al.* (1999) elucidated the fundamental temperature responses of

early-season apple fruit growth that directly affect fruit size at harvest (Plate 10 1). Fruit expansion rates were highly temperature-responsive only during the cell-division fruit-growth phase lasting c. 40 days after pollination (DAP). Fruit expansion was approximately 10 times greater at a mean temperature of 20°C than at a mean of 6°C. The fruit expansion rate responded to changes in mean temperature rather than to the maximum/minimum differential. The duration of fruit cell division in fact appeared to be inversely related to mean temperature, being prolonged under cooler conditions. A comparison of mean expansion rates of four cultivars across a gradient from 6 to 20°C also suggested genetic differences. Field studies in three regions of New Zealand over three seasons monitored fruit growth of 'Royal Gala' under conditions that minimized crop competition. Regression analysis using fruit growth intervals after pollination explored how well temperature accumulation (GDD, base temperature 10°C (GDD₁₀)) was related to seasonal differences in fruit weight (Stanley *et al.*, 2000). The strongest relationship occurred between fruit weight at 50 DAP and GDD₁₀ at 50 DAP, accounting for 71% of the variance. These field-measured fruit growth responses closely agree with the controlled-environment responses from Warrington *et al.* (1999). However, temperature accumulation over increasing intervals from 30 DAP and including the complete fruit growth period proved too inaccurate for robust prediction of fruit weight at harvest. Early-season temperature effects on fruit growth are clearly integrated with other influences, such as competition among fruits, but the relative contribution of each factor to fruit size at harvest remains unquantified. However, it seems likely that, in commercial production, a reduction in crop density during the cell-division growth phase should invoke greatest fruit size responses when higher temperatures coincide with this early crop thinning

There is good evidence that temperatures experienced during early fruit growth affect the rate and timing of fruit ripening. There may therefore be an impact on fruit growth and size at maturity if the duration

from bloom to harvest varies greatly. Several controlled-environment studies showed that fruit-maturity indicators, such as changes in starch content, firmness, background colour, red blush and ethylene production, were accelerated by higher temperatures in the first 6 weeks of fruit growth (Tromp, 1997; Warrington *et al.*, 1999). However, each maturity variable did not respond to the same degree. The field studies by Stanley *et al.* (2000) also found a strong correlation between GDD_{10} to 30 DAP and time from pollination to harvest. Tromp's study showed the early temperature influence on ripening to be more influential than high temperatures applied around the time of onset of maturity. All these studies were carried out on trees with their cropping level minimized.

Fruit growth and size at harvest appear to be largely unaffected by temperature in the period beyond 40 DAP (Warrington *et al.*, 1999), at least when crop load is minimized. However, unpublished controlled-environment studies have raised the possibility that temperature $\times$ crop-load interactions during the fruit-expansion growth phase may be important in determining fruit development and fruit characteristics at maturity (D.S. Tustin, unpublished).

10.9 High Summer Temperatures

Excessively high temperatures can result in sunburn on the skin of the apple fruit, although in minor cases this results in a clearing of the colour from the epidermal tissues (sun tinting), in more serious cases tissues can collapse into a brown sunken patch on the skin, rendering the fruit unsaleable and more likely to suffer further damage due to splitting or fungal attack. Current methods of control of sunburn rely on reducing the temperature of the fruit skin: (i) by shading, either by allowing a light leaf cover exterior to the fruit, the use of hail netting or more recently sprays of reflective kaolin; or (ii) by sprinkling water on to the apple trees and dissipating heat by evaporative cooling. Apple fruit have a considerable thermal mass and by virtue of their size are not able

to dissipate heat as well as leaves. Consequently the skin temperature of an apple exposed to strong sunlight can be as much as 13–14°C higher than air temperature (Thorpe, 1974). Sunburn of apple fruit was observed by Bergh *et al.* (1980) when the skin temperature of apple fruit exceeded 50°C. This occurred when air temperature exceeded 36°C. It is not known if tissue sensitivity to damage alters with fruit development or even why some cultivars show less sunburn damage than others (e.g. 'Royal Gala' is less sensitive than 'Braeburn' or 'Granny Smith'), all of which suggests a fruitful area for future research.

High summer temperatures can also reduce the production of flower buds. Controlled-environment studies by Jonkers (1984) and Tromp (1976) showed that high daytime temperatures (25–27°C) reduced flower formation. In the light of the temperature effect on net canopy CO_2 exchange, this could be interpreted as a lack of available carbohydrate, particularly considering that these trees were grown in controlled environments, where irradiance levels are often below those experienced in the field. Although the carbohydrate requirement for flower-bud development may be small compared with that of other sinks, such as fruit, the tree may allocate carbohydrate preferentially to the other sinks. Shading trees also reduces flower-bud production, possibly through the same mechanism.

10.10 Root Growth

Rogers (1939) suggested that the onset of root growth of apple occurs at 6.2°C. The periodicity of root growth, other than during the winter, seems to be much more related to the activity of the aerial part of the tree rather than to soil temperature. Work in the root observation laboratories at East Malling found a bimodal pattern of root growth, with the first flush of growth in May/June followed by a later flush in August/October, separated by a major peak in shoot growth (Atkinson, 1980). There has, however, been considerable work on the effects of high soil temperatures on root growth in subtropical

areas. Gur *et al.* (1972) reported that root growth of apple trees was reduced at root temperatures of 30°C and above and serious damage to the leaves occurred at root temperatures of 35°C and above, due to the transport of products of anaerobic respiration from the roots.

10.11 Shoot and Leaf Growth

The effect of temperature on shoot and leaf growth has received much less attention than its effects on fruit development. In a study examining the effects of temperature on shoot development, Tromp (1992) found that the production of sylleptic shoots ('feathering') was improved as soil temperature increased to 28°C while air temperature was maintained at 20°C.

Johnson and Lakso (1985) found that shoot growth of apple was linearly related to accumulated day-degrees above 4°C, with a slope of 0.08 cm GDD⁻¹. This rate was quite constant among different cultivars, rootstocks, tree age and pruning severity. Leaf area per shoot was also linearly related to accumulated GDD. In contrast to the results with shoots, there was considerable variation among cultivars in the slope and intercept of this relationship.

10.12 Synthesis of Temperature Effects in Models

There are two major techniques that have been used to examine the effect of temperature on tree growth, development and yield: the first uses correlation techniques with long-term data sets of phenology, yield and weather data, while the second uses controlled-environment facilities specifically to examine temperature effects directly. Most work with apples has made use of the former approach, as the size of cropping trees has limited controlled-environment room studies to only a few locations (e.g. The Netherlands and New Zealand). Jackson and Hamer (1980) correlated the average UK yield of 'Cox's Orange Pippin' to temperature, after removing a long-term trend of

increasing yields. They found that the yield of 'Cox's Orange Pippin' was: (i) negatively related to high temperatures in February, March and April; and (ii) positively related to high temperatures after bloom and again in June. Typically in Kent, full bloom of 'Cox's Orange Pippin' would be early May. About 80% of the year-to-year variation in UK average yields could be explained by their relationship, which considering the use of only one weather data set – that recorded at East Malling – was particularly encouraging. It is important to note, however, that the majority of the 'Cox' crop in England is grown in Kent. The negative effect of warm temperatures before bloom was not associated with earlier flowering resulting in more frost damage. The positive effect of high temperatures directly after bloom was related to enhanced pollen-tube growth. This correlation of yield and temperature was further refined by Miller (1988), also at East Malling (Equation 1), using a data set up to 1987, where she replaced the mean maximum temperature in February–April by mean day-degrees above 4.5°C and used a curvilinear relationship for the long-term trend of yield:

$$Y = -5.27 + 0.5t - 0.009t^2 - 2.35DD - 0.51PT + 0.93J \quad (1)$$

where Y = mean UK yield of 'Cox's Orange Pippin' (t ha⁻¹); t = number of years from 1948; DD = mean day-degrees above 4.5°C during February, March and April; PT = number of days to complete pollen-tube growth; and J = mean maximum temperature in June.

Miller (1988) also examined the causes of the negative effects of warm spring temperatures by using mobile greenhouses. Warm spring temperatures resulted in earlier flowering, as expected, but the effective pollination period was also reduced due to poorer ovule longevity, and this resulted in poorer fruit set. Although this work was done with 'Cox's Orange Pippin' in England, Lakso (1994) found that the relationship used by Jackson and Hamer (1980) gave a good relationship to apple yields in New York State, suggesting that these effects are more widely applicable to other cultivars and locations.

Rather than relying on correlation studies, several more mechanistic models of apple tree growth have been developed. The great advantage of such models is that they mathematically relate the growth of all the parts of the tree to the environmental variables. Consequently, within the model, temperature and solar radiation can be altered independently at different stages of growth and the outcome predicted. In recent work, Lakso *et al.* (2001) used a model to predict net CO₂ assimilation by apple trees in New Zealand, Washington State and New York State. The authors draw attention to the mild temperatures in New Zealand extending the leaf-area duration after the harvest period. In some of his earlier correlation studies between temperature and annual yields in New York, Lakso (1994) found that mean temperature between harvest and leaf fall had a positive effect on yield in the following season, possibly via extended leaf-area duration. Wagenmakers (1996) has modified the crop growth model SUCROS, developed by the group at Wageningen, for apple trees. The results from this model predicted that warm springs were favourable for a rapid development of leaf area, resulting in increased light interception and CO₂ assimilation. In contrast, higher temperatures in mid- to late summer before harvest resulted in high maintenance respiration and reduced fruit growth.

10.13 Fruit Quality

Although fruit colour development on red cultivars of apples is strongly dependent on cultivar, fruit maturity, light, nutrition and crop load, there is also a pronounced effect of temperature (Saure, 1990). In general, cooler night temperatures favour the development of red colour – for example, Creasy (1968) found an inverse relationship between average temperature and anthocyanin formation in 'McIntosh' apples. The relationship between colour formation and temperature also seems to vary between experiments done with detached fruit and those done with whole trees with attached fruit.

Temperature during the 4–6 weeks immediately preceding harvest can influence the quality of the fruit at harvest and its storage potential. Cooler temperatures result in less water-core development and a reduced susceptibility to superficial scald (Bramlage, 1993) but a higher risk of core flush in 'Cox's Orange Pippin' and 'McIntosh' and low-temperature injury in 'Bramley's Seedling', 'Cox's Orange Pippin', 'Jonathan' and 'Yellow Newtown' (Sharples, 1984). Less scald after storage was observed where fruit had received 100–150 h below 10°C before harvest and little scald developed when the fruit had received more than 150 h (Merritt *et al.*, 1961). In the UK, however, increased incidence of scald has been related to increasing soil-moisture deficit from late July to early September with the cultivar 'Edward VII' (Sharples, 1984). Sharples adds a key general comment that the incidence of storage disorders is frequently related to fruit maturity at harvest, and relationships to temperature, for example, may be confounded with effects on fruit maturity if picking date is not adjusted accordingly.

10.14 Conclusions

Temperature has a profound effect on all aspects of apple tree physiology. At the extremes, high or low temperatures can cause death, while, at intermediate temperatures, all physiological processes are affected. It must not be forgotten, however, that tissue temperatures within the plant vary widely from exposed to shaded tissues and from tissues above ground to tissues underground, where there is also a range of soil temperatures. The response of the whole plant to temperature is the result of the effect of temperature on each part of the plant and the interactions among those tissues. With the changes in climate associated with global warming, it is even more imperative to elucidate the response of the apple tree to temperature to be able to predict the effect of increasing temperatures in order to guide orchardists in their choice of cultivars and to alert them to a likely increased or decreased incidence of problems.

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11 Selecting the Orchard Site, Site Preparation and Orchard Planning and Establishment

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11.1 Selecting the Orchard Site

11.1.1 Geographical and climatic considerations

The cultivated apple has its origin in the Republic of Kazakhstan (see also Chapter 1), from which it has spread throughout the world (Hokanson *et al.*, 1997). It is classified as a temperate fruit tree, which indicates that it is deciduous and requires an extended cold period (chilling requirement) for buds to break for both foliation and flowering. Apple trees can survive in many parts of the world, but most are grown between latitudes 30° and 50° north and south. The primary limiting factor in apple production at latitudes lower than 30°, north or south, is the lack of adequate chilling in winter to break rest (endodormancy). Additionally, the excessively warm temperatures at such latitudes have negative effects on fruit colour and quality. At greater than 50° latitude, north or south, the major limitations related to temperature are damage by the coldest nights of winter and inadequate length of growing season. At all latitudes, there are sizeable effects of other factors, such as elevation and proximity to large bodies of water

11.1.1.1 Elevation

Temperatures are dramatically affected by elevation; a rule of thumb is that day and night temperatures decline by about 3°C for each 500 m increase in elevation. A striking example of this effect on temperatures is found in South America. Belem, Brazil, is 19 km from the equator at an elevation of about 10 m and has a mean annual temperature of 29°C. Quito, Ecuador, also about 19 km from the equator but at an elevation of 2835 m has a mean annual temperature of 13°C. The effect of elevation is present regardless of latitude and plays a vital role in determining what crops can be grown successfully. Therefore, as latitude decreases, commercial apple orchards are planted at higher elevations. For example, in the eastern USA, apple orchards south of Virginia are mostly in the mountains, such as in western North Carolina and north-western South Carolina

and Georgia. In Mexico, commercial quantities of apples are grown at high elevations in the northern states of Chihuahua, Durango and Coahuila (Herrera, 1984).

11.1.1.2 Proximity to oceans or lakes

Another factor of considerable importance is proximity to large bodies of water, particularly when the prevailing winds come over the water. Apple industries exist in Ontario, Canada, primarily in the southern regions of the province along Lake Erie and Lake Ontario. Likewise, apple areas exist on the leeward sides of the Great Lakes in Michigan and New York. Nova Scotia has a significant apple industry because of the moderating effects of the Bay of Fundy and the Atlantic Ocean. There is very little apple production in the middle Canadian provinces of Alberta, Saskatchewan and Manitoba because the climate is continental; their winters are so cold that they severely restrict apple production. There is an important apple industry in interior valleys of southern British Columbia because of the moderating influence of the Pacific Ocean and large valley lakes, such as the Okanagan (Plate 11.1).

Bodies of water serve two vitally important roles in minimizing frost damage. In the spring, water warms up more slowly than the adjacent land surfaces. The prevailing winds are cooled as they pass over the cold water in the spring. As the cooler air passes over the adjacent apple trees, bud development is delayed, thus decreasing the probability of spring frost injury. In the autumn, the water cools more slowly than the land and thus air masses are warmed as they pass over it. This warmer air delays the onset of early-autumn freezes. This lake effect is of consequence for only a few kilometres from the lake but accounts for the large concentration of orchards and vineyards along the leeward sides of lakes or other large bodies of water. Since relatively mild autumn frosts (−1 to −3°C) are not particularly detrimental to leaves and apples remaining on the tree, this extension of the growing season is much more valuable to a grape grower, whose crop is severely damaged by even a light frost.

11.1.1.3 Chilling requirement

The apple is a fruit tree in the general category of temperate plants, which are characterized as requiring an annual cold period to satisfy their 'chilling requirement'. If the chilling requirement is not satisfied, the buds will not open; if the chilling requirement is partially met, the buds will open sporadically and both the bloom and harvest periods will be abnormally extended. Most apple cultivars require between 1000 and 1200 h of chilling in the range of 4–7°C. Temperatures below 0°C or above about 10°C do not provide chilling and may actually negate previously accumulated chilling hours. Because of this, the chilling requirement of a particular cultivar may well be satisfied earlier in a middle latitude than in a more poleward latitude. In some parts of the world where winter temperatures are so warm as to barely meet the chilling requirement (as in parts of California), the presence of frequent morning fog delays the daily rise in temperature of buds, thus enabling the accumulation of adequate chilling hours.

In warm areas where the chilling requirement is not met, rather extreme treatments can induce the buds to grow despite the lack of chilling (Edwards, 1987). According to Janick (1974), cultivars including 'Rome Beauty' and 'McIntosh' as well as local cultivars can be grown in areas of Indonesia (east Java) at latitudes of less than 10°S and elevations of 700–1200 m. The maximum, minimum and mean annual temperatures are 31, 22 and 26°C, respectively. Through the use of complete defoliation approximately 1 month after harvest, a new growth and fruiting cycle is initiated. Flowering occurs approximately 1 month after the trees are defoliated. The cycle is repeated to induce two crops per year. In subtropical regions, the chilling received is inadequate and various treatments have been developed to supplement the chilling received. In addition to the selection of low-chilling cultivars, such as 'Anna' and 'Ein Shemer', several chemicals have proved to be at least somewhat effective. These include mineral oil, dinitro-*o*-cresol, potassium nitrate, thiourea and cyanamide, as well as gibberellins and cytokinins (Erez, 1987).

11.1.1.4 Length of growing season

The length of the growing season, also referred to as the number of consecutive frost-free days, varies greatly with latitude and depends upon a number of factors. There is a considerable impact of large bodies of water on spring, autumn and winter temperatures. In general, lakes extend the growing season within a few kilometres of the leeward side. Another very important factor is elevation, in this case relative to sea level rather than above the adjacent terrain (as will be described below under spring frost potential). In very poleward countries, such as Denmark, Norway and Sweden, the moderating effect of the surrounding oceans offers some protection from extreme winter cold, but the growing seasons are very short. The number of days from blossoming to harvest for apple cultivars ranges from 75 or 80 to over 200. Short-season cultivars can be grown widely, but those requiring more than 180 days are restricted to regions with long growing seasons.

11.1.2 Site selection: temperature

In the selection of a site on which to establish an orchard, climatic considerations are of utmost importance. In the remainder of this chapter we discuss climate from a somewhat local perspective. Arguably, the most critical climatic factor to consider in selecting an orchard site is temperature and, among the several aspects of temperature, none approaches the importance of the likelihood of spring frost damage. Unfortunately, spring frost damage to apple flowers and young fruit is an all-too-frequent occurrence (Plate 11.2). There have been a great many approaches devised to minimize spring frost damage (see Chapter 20), but, by an immense margin, the best frost-control technique is good site selection! There are obviously many other considerations, such as soil, in selecting a good orchard site, but, if the site is 'frosty', none of the other attributes of the site will overcome this one all-important weakness.

11.1.2.1 Radiational freezes

Considerable information can be gained by visually evaluating the site under consideration. Most important is its elevation, not above sea level but above the adjacent terrain. The vast majority of frost damage occurs under radiational freeze conditions. On relatively clear, calm, spring nights, heat is lost by radiation from plants, soil and other surfaces exposed to the cold sky. The lower layers of air are cooled by losing heat, by conduction, to these exposed surfaces, which have dropped below air temperature. As air is cooled, it becomes more dense (heavier) and therefore settles on the ground, flowing ultimately into low areas; this settling of cold air has led to the term 'frost pocket', used for low-lying areas that are particularly subject to frost damage (Fig. 11.1).

11.1.2.2 Temperature inversions

As lower air layers lose heat to cold surfaces, these layers become colder than the air above, so air temperature increases with altitude. This phenomenon is called a 'temperature inversion' because it is the reverse of the

normal situation during the day when the air temperature declines with increasing altitude. The 'top of the inversion' is the altitude at which the air is warmest. Both wind machines and helicopters are used to mix the warm air in the upper portion of the inversion with colder air at tree level in the orchard (see also Chapter 20).

On a commercial scale today, orchard sites are selected on the basis of minimal danger of radiational frost damage, but they must also be on a slope that does not preclude the use of modern equipment. Since apple trees thrive in a permanent-sod soil-management programme (often supplemented with a herbicide strip), such orchards can be successfully grown on steeper slopes than peaches, which are usually grown with at least some cultivation. The degree of slope that can be tolerated will vary with row spacing, tree size and especially the type of equipment available (Plate 11.3). In different parts of the world, these climatically ideal fruit sites may have somewhat different characteristics. In many regions, orchard sites are selected on sloping land above large valleys, on knolls in rolling terrain and on terraces above rivers.

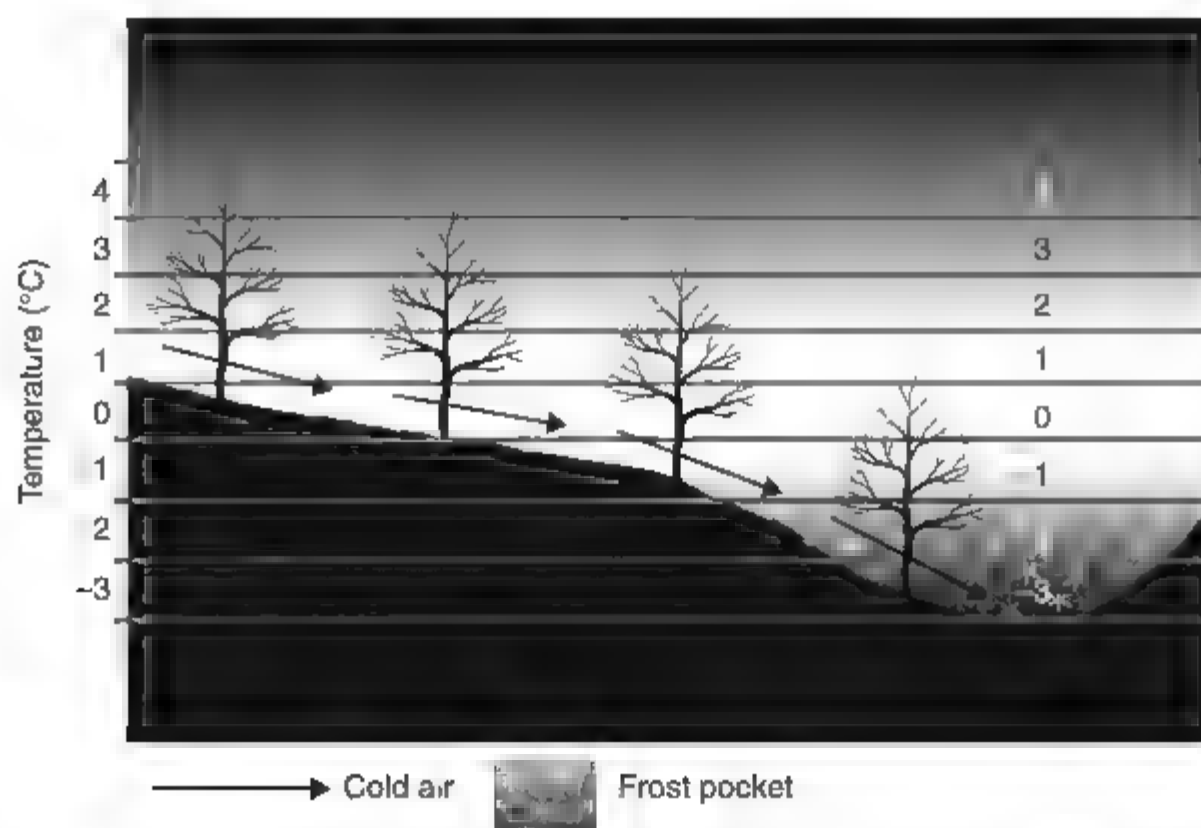


Fig. 11.1. During a radiational freeze, layers of cold air along the ground flow downhill, settling into low-lying areas called 'frost pockets'

11.1.2.3 Advective freezes

Apple crops are sometimes lost to cold temperatures associated with an 'advective freeze', which is a cold event resulting from the invasion of a large cold air mass accompanied by high winds (see also Chapter 20). Since such conditions preclude the formation of a temperature inversion, wind machines, helicopters and other methods dependent upon an inversion are ineffective. Although much less frequent than radiational freezes, the occurrence of an advective freeze is devastating because there is little that can be done to lessen its impact. Furthermore, the sites selected to minimize danger from radiational freezes are particularly vulnerable to advective freezes because of increased exposure.

11.1.3 Winter injury

Winter injury to apple trees can vary both in when it occurs and in what trees are injured, depending on a variety of factors (see Chapter 10). One type of winter injury typically occurs in mid- to late winter to mature bearing trees that have reached their maximum hardiness, but are injured because of the extreme cold (often in the range of -30° to -35°C). With bearing trees, previous stress resulting from a particularly heavy crop, drought, nutrient deficiency or premature defoliation can lessen midwinter cold-hardiness. A second type of injury consists of damage in late autumn to young trees that have not yet reached their maximum hardiness. Because of either heavy or late nitrogen applications, young trees tend to grow relatively late in the summer and are therefore delayed in reaching maximum hardiness compared with an older bearing tree, which ceases vegetative growth earlier in the summer.

11.1.3.1 Hardening

The physiological processes involved as perennial plants develop cold-hardiness have been studied extensively, but the exact mechanisms remain elusive. The hardening process starts only after vegetative growth has ceased and is induced by decreasing day

length and declining temperatures. Sub-freezing temperatures are required to effect the later stages of the hardening process.

Another factor that contributes to the occurrence of winter injury is the variation in temperatures before the cold event. A freezing event preceded by a warm period is far more damaging than continuously cold temperatures. The development of hardiness is a gradual process that proceeds over a period of weeks, but even a temporary warm period late in winter can lead to rapid loss of hardiness. For this reason, winter injury to apple trees is more common in winters with wide temperature fluctuations than in winters with comparably low but continuously cold temperatures.

11.1.3.2 Trunk injury

Whether it is a young tree damaged in the autumn or an old tree damaged in midwinter, the injury is most often to the trunk and lower scaffold limbs. These are the last tissues to harden and therefore the most likely to be injured. Injury is frequently apparent as a splitting of the bark (Fig. 11.2). If the bark is reattached to the trunk or branch soon enough to avoid death of the vascular cambium by desiccation, the tree can be saved. If, however, the cambium dries out on a large part of the trunk, the only way to save the tree may be to utilize either bridge grafting or inarching (Hartmann *et al.*, 1990). With bridge grafting, the goal is to replace the trunk; with inarching, the goal is to replace both the trunk and the root system. In severely cold periods, the entire trunk may split open, which allows little hope of survival.

11.1.3.3 Other factors

There is considerable variation in the cold-hardiness of both rootstocks and scion cultivars, and this can have important practical implications. The rootstocks selected in breeding programmes such as those in Poland (P series) and Russia (Budagovsky series) have been selected to a large degree on the basis of cold-hardiness because winter survival is such a vitally important issue in those areas (Ferree and Carlson, 1987). Winter survival is uppermost in the selec-



Fig. 11.2. The splitting of bark on the trunk of apple trees is a common symptom of winter-cold injury. It may occur from a moderately cold temperature (-10°C) in mid-autumn, prior to the development of maximum hardiness, or from severe cold (-30°C) in midwinter.

tion criteria of apple breeders in areas with very cold winters, such as Minnesota; for apple breeders in warmer regions, winter-hardiness is of much less concern.

Severity of winter injury within a region tends to vary little due to local factors such as elevation, because winter cold events are usually associated with windy conditions, much like an advective freeze in the spring. In winter there are therefore not the large microclimatic effects that are so important during radiational freezes in the spring.

11.1.3.4 Root injury

The roots of apple trees are considerably less cold-hardy than are the above-ground portions. Much of this difference is because roots do not go into rest and are active during winter when soil temperatures are above a minimum of about $6-7^{\circ}\text{C}$. Secondly, since roots are not exposed to temperatures as low as are the above-ground portions, they do not develop nearly as much hardiness. If an apple root is exposed to the same gradually declining temperatures as the above-ground parts of the tree, the hardiness of the root can become equal to that of a branch. A continuous snow cover provides considerable protection for the roots of apple trees by insulating the soil from excessive heat loss. Because snow is made up of about 80% entrapped air, it is an excellent insulator. Winter injury to the roots of apple trees is far more likely to occur in areas with an 'open winter' without snow cover than in more northern regions, which may be colder but have more snow on the ground.

11.2 Soil Considerations

General observations from many fruit-growing regions indicate that apple trees grow well on a range of soils. However, the extra effort and cost required to manage difficult soils indicate that considerable effort should be devoted to investigating and understanding limiting soil properties and their potential amelioration at a site prior to incurring the additional costs associated with planting.

11.2.1 Soil physical properties

It is generally acknowledged that poor soil physical properties require paramount consideration because they are more difficult and sometimes impossible to improve as compared with inadequate soil fertility and chemical conditions.

11.2.1.1 Soil texture

The texture of a soil refers to the proportion of different mineral particle sizes in the soil. Size classifications from smallest to largest

include clay (< 0.002 mm), silt (0.002–0.05 mm), sand (0.05–2 mm) and gravel (2–80 mm). The percentage by weight of sand, silt and clay in a given soil is often represented in a texture triangle from which soils can be grouped into similar textural classes ranging from fine to coarse (Fig. 11.3). The textural grouping influences several soil properties important to apple production, including potential water-storage capacity, perviousness to internal water transmission, aeration and nutrient-exchange capacity (Table 11.1). A special consideration regarding both soil texture and soil structure is the ability of the soil at a site to support the year-round passage of orchard equipment ('trafficability'). Soils should be able to withstand compaction and be free of surface flooding. Large gravel, cobble and stones (> 2 mm diameter) can improve drainage and warming of some fine-textured soils but can be serious impediments to soil cultivation and even tree planting.

11.2.1.2 Soil structure

In most soils, individual particles of sand, silt and clay are aggregated into larger-scale structural units, which create a network of

pores and fissures throughout the soil profile, allowing easier air and water movement (Fig. 11.4). A stable structure with a wide range of pore sizes is desirable for apple production. Serious growth problems can arise when compacted layers with high bulk density and associated reductions in air-filled voids occur in the main rooting zone. Such layers can arise near the surface in traffic rows of old orchards subjected to frequent passes of tractors and sprayers under moist soil conditions. Some soils can also contain naturally compacted subsoil 'hardpans' resulting from layers enriched in calcium, iron or clay particle sizes.

11.2.1.3 Soil depth

Apple tree performance is affected by the depth of the soil to which unrestricted root growth can occur. Possible barriers to root development include seasonal or year-round high water-tables, compacted layers, bedrock or abrupt textural changes to much finer or coarser particle size in the subsoil. The depth of unrestricted root penetration by apple can be quite variable, with a 1–2 m depth most common, although most roots are generally located within the surface 0.8 m depth (Atkinson, 1980). A greater potential rooting depth can enhance tree growth and production by increasing tree access to nutrients and water. This can be particularly important in coarse-textured soils, which often have limited nutrient- and water-holding capacities (Table 11.1). Although some of the limitations of shallow soil depth can be overcome by effective irrigation or soil amendment, it is a well-known phenomenon that severe restrictions in rooting volume reduce tree vigour and fruit size in spite of modifications to improve nutrient and water supply to the plant. It is therefore important to have a knowledge of effective soil depth prior to planting.

Shallow soil depths can be less limiting to apple tree performance for scions on rootstocks that are already naturally dwarfing. However, care must be taken to optimize soil physical and chemical conditions in what is a more limited soil volume that offers less buffering against various environmental stresses.

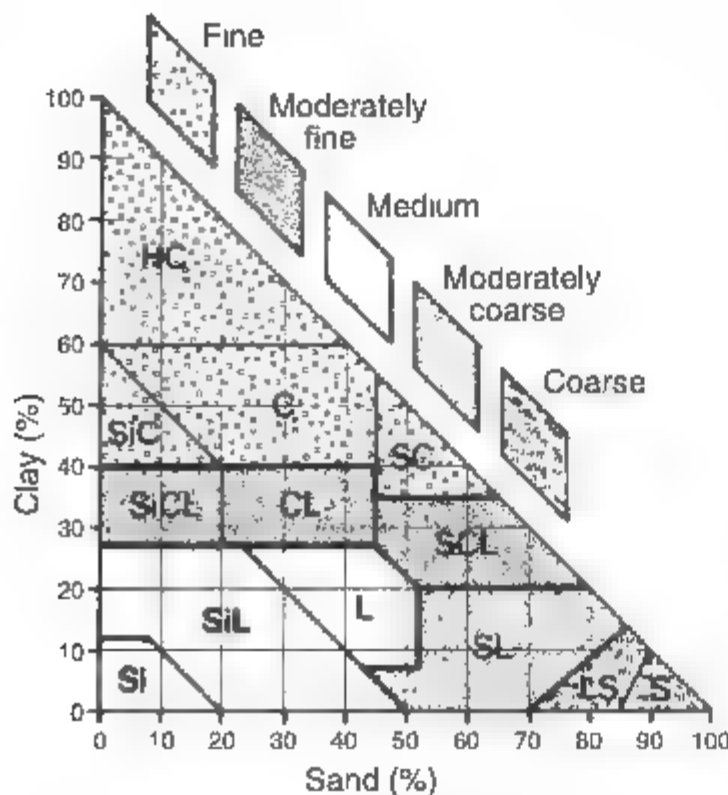


Fig. 11.3. Percentage of clay and sand in the main textural classes of soils; the remainder of each class is silt (adapted from Association of British Columbia Grape Growers, 1984).

Table 11.1. General characteristics of main soil textural groups (adapted from Association of British Columbia Grape Growers, 1984).

Textural group	Soil textures	Typical water storage capacity (cm m ⁻¹)	Perviousness	Soil aeration	Typical nutrient exchange capacity (cmol (positive charge) kg ⁻¹)	Trafficability (when wet)
Coarse	Gravel (G) Sand (S)	Very low–low (2–10)	Rapid (soil remains wet for only hours after wetting)	High	Very low (< 5)	Good
Moderately coarse	Loamy sand (LS) Sandy loam (SL)	Moderate (10–14)	Rapid–moderate	High–moderate	Low (5–15)	Good
Medium	Loam (L) Silt loam (SiL) Silt (Si)	Moderate–high (17–21)	Moderate (soil remains wet for days after wetting)	Medium	Medium (15–25)	Moderate
Moderately fine	Clay loam (CL) Silty clay loam (SiCL) Sandy clay loam (SCL)	High (≥ 20)	Poor (soil remains wet for weeks after wetting, many small pores)	Medium–low	High (20–50)	Poor
Fine	Silty clay (SiC) Sandy clay (SC) Clay (C) Heavy clay (HC)	High (≥ 20)	Poor	Low	High (20–50)	Very poor

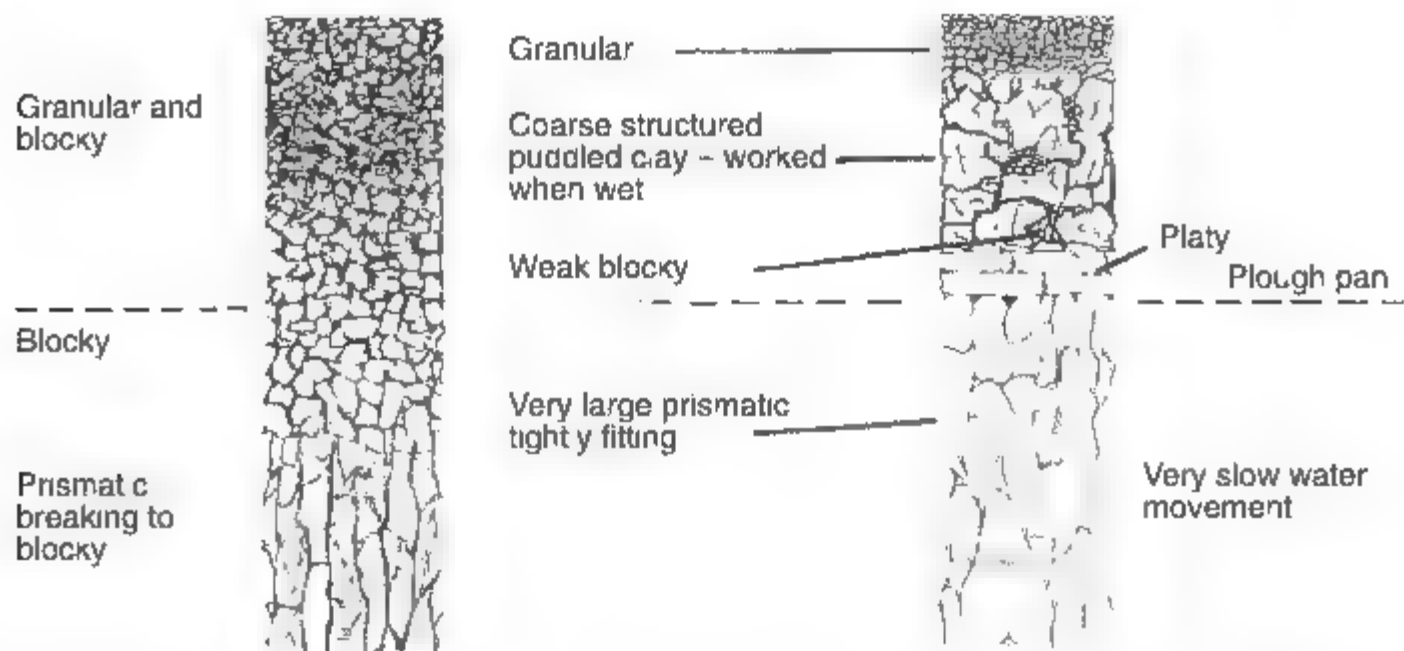


Fig. 11.4. Example of well-structured soil (left) and poorly structured soil (right) (adapted from Davies *et al.*, 1972)

11.2.1.4 Soil water relations

The capacity of soils to store water available to plants varies considerably with soil texture (Fig. 11.5). Water availability is usually expressed as the difference in water content between field capacity (FC) and the point at which plants wilt permanently (PWP). FC is the water content after drainage of saturated soils has become negligible. The drained pore space under this condition provides air

space for the aeration of roots. PWP is the water content at which plants can no longer extract adequate water to regain turgidity in the dark. Local soil survey reports often contain available water-content values for various soils by measuring the difference in water content between soils equilibrated at pressures between 0.03 MPa (FC) and 1.5 MPa (PWP). Such information can be valuable when selecting planting sites for

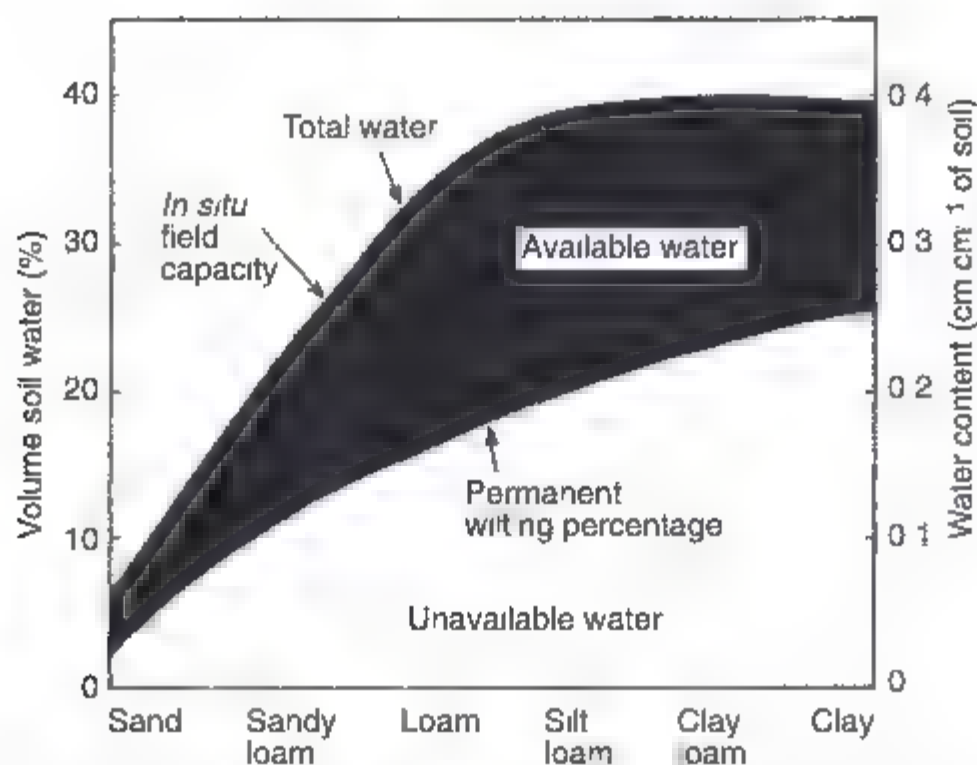


Fig. 11.5. Relative amounts of available and unavailable water in soils ranging in texture from sands to clays. Amounts of water expressed as percentages of soil volume (left) and cm of water per cm of soil depth (right). (From Kramer and Boyer, 1995.)

apple orchards. Growth limitations from inadequate water-storage capacity or the need for supplemental irrigation is more likely to occur on coarse-textured soils.

Also important for apple trees is good soil aeration for proper root functioning. Aeration is not often a problem in coarse-textured soils but can seriously limit growth in fine-textured soils. Poor internal drainage through soil profiles can result in excessive waterlogging, depriving roots of oxygen and creating saturated soil conditions favourable for the development and spread of pathogenic fungi, such as *Phytophthora* root and crown rots, especially on susceptible rootstocks.

Good soil drainage is thus preferable when locating apple orchards. Sites susceptible to waterlogging or even surface ponding of water can occur in low-lying areas where water tables are high year-round or only during periods of excess moisture, as in the spring after snow-melt or when evapotranspiration is low and precipitation high. Such locations may occur because of restriction of water movement through impermeable subsoils or may result from seepage of water (and sometimes excessive fertilizers and other soluble salts) from other locations in the landscape. Although it is possible to remedy inadequate drainage at some sites by installation of tile drains, this can be an expensive solution.

11.2.2 Soil topography

The location of a potential orchard site within the general landscape can affect subsequent orchard performance. Flat or gently sloping sites are ideal for the operation of equipment. Other considerations include location with respect to prevailing winds and local air flows. Exposed ridges and narrow valleys subjected to persistent strong winds can result in disruption in the timing and accuracy of spray application and can even distort tree shape. Tree windbreaks have been effectively planted as barriers to reduce wind effects on orchards, although edge rows of apple trees are susceptible to the competitive effects of vigorously growing trees in nearby wind-breaks.

As previously indicated, landscape location can result in more favourable microclimate conditions, which can enhance orchard performance by reducing the risk of spring-frost damage.

11.2.3 Soil chemical properties

11.2.3.1 Nutrient content

The availability of many plant nutrients, including major elements, such as phosphorus, potassium, magnesium, calcium and sulphur, and trace elements, such as zinc, manganese, boron, iron and copper, can be readily determined in various extracts from representative composite soil samples collected at a prospective orchard site. Since apple is relatively deep-rooted compared with many annual crops, composite samples need to be collected to a sufficient depth to characterize the anticipated major rooting zone. Thus, in addition to samples collected from the surface layers (to 20 cm depth), useful information can be obtained from samples collected to represent 20–40 and 40–60 cm depths. The usefulness of the values determined often depends upon the extent of local research to calibrate tree response to fertility parameters. Usually much less information is available for apples than for annual agronomic and horticultural crops. However, it can be extremely useful to determine if a site has exceptionally low or high availability of important plant nutrients and how availability of these nutrients changes with depth. Ameliorative fertilizer applications can thus be made prior to planting when relatively immobile nutrients, such as phosphorus and potassium, can be ploughed into the potential root zone. Phosphorus seems to be a particularly important nutrient for establishing apple trees. Improvement in first-year growth of apple trees has been reported following applications of relatively high rates of especially well-mixed ammonium phosphate fertilizer compounds directly in the planting hole or fertigated directly into the zone of newly emerging roots (Neilsen, 1994). Nitrogen,

however, is the major fertilizer to be applied in most orchards but, at present, N-fertilizer recommendations are adjusted on the basis of plant response or leaf analysis rather than based on soil N assessment.

11.2.3.2 pH

An ideal soil pH range (as measured in water) for apple is 6.5–7.0, although there has been limited documentation of this information. It is, however, known that below pH 5.5 the solubility of manganese and aluminum ions increases rapidly in most soils. Manganese toxicity has been associated with internal bark necrosis (Fig. 11.6) and reduced vigour of newly planted trees (Hoyt and Neilsen, 1985). Manganese toxicity problems are especially serious for 'Delicious' and cultivars with 'Delicious' parentage but have been observed on several other cultivars, including 'Golden Delicious' and 'McIntosh' (Berg *et al.*, 1958). Although a low pH is the

most important soil factor affecting manganese solubility, waterlogged soils, regardless of pH, can also have an increased incidence of manganese-induced internal bark necrosis (Grasmanis and Leeper, 1966). Soluble aluminium is also highly toxic to most plants, even at a low concentration, acting to inhibit root elongation and branching (Scott and Fisher, 1989). Aluminium is toxic to apple seedlings at concentrations as low as 6.5×10^{-6} M (175 ppm.) in solution (Kotze *et al.*, 1976).

In alkaline soils, where pH values exceed 7.0, other growth limitations have been observed. For example, trees planted on calcareous soils, where pH is frequently 7.5–8.5, can have growth-limiting nutrient deficiencies resulting from decreased availability of phosphorus and several trace elements, including iron, zinc and manganese. Alkali soils have pH values exceeding 8 and high sodium contents, which adversely affect soil structure, resulting in dense and poorly aerated soils.

As will be discussed later, considerable research has been conducted on ways to overcome adverse soil pH conditions. By far the best time to make such adjustment is prior to planting, when concern for existing trees will not limit the ability to work amendments to sufficient depth.

11.2.3.3 Salinity

Saline soils can exhibit a wide range of basic pH values and can have high concentrations of salts, such as sodium, chloride and boron, which can be toxic to apple trees. Soils with high salinity values in what will be the major rooting zone of a proposed apple orchard can limit tree establishment. Considerable information available from research organizations (such as the USA's Salinity Laboratory in Riverside, California (Maas, 1987)) indicate that apple, like most perennial woody fruit crops, is susceptible to yield and growth reductions as soil salinity increases. Soil salinity is usually measured as the electrical conductivity of saturated extracts of composite soil samples representing the main root zone. Values are expressed as decisiemens per metre (dS m^{-1}) and val-



Fig. 11.6. 'Starkrimson Delicious' apple tree on M.26 rootstock exhibiting severe internal bark necrosis resulting from manganese toxicity.

ues much exceeding 1 dS m^{-1} (approximately 640 p.p.m. (mg l^{-1}) salt in soil solution) have been reported to reduce the yield and growth of apple. Excessive soil salinity can occur in landscape locations in semiarid regions where seepage waters accumulate, but can also be induced in smaller soil volumes by over-application of soluble fertilizers to the roots of newly planted apple trees.

11.2.4 Soil chemical contamination

Accumulation in the soil of persistent chemical residues from previous land-use activities has the potential to adversely affect growth of newly planted trees. For old orchard sites, for example, high lead arsenate concentrations in the root zone can be phytotoxic to apple trees (Benson, 1976). Lead arsenate (and related compounds) was widely used as an insecticide, particularly for control of codling moth (*Cydia pomonella* L.) for about a 50-year period, ending about the time of the introduction of the synthetic organic insecticide dichlorodiphenyltrichloroethane (DDT) following the Second World War (Peryea, 1998). In Washington State, growth problems with young apple trees are predicted when total arsenic concentrations in the root zone exceed 50 p.p.m. (Benson, 1968). Remedying such a situation can be difficult without the addition of uncontaminated soil, particularly in and near the planting hole where newly forming roots emerge.

It is also known that applications of residual herbicides, such as terbacil (3-tert-butyl-5-chlor-6-methyluracil), diuron (3-(3,4-dichlorophenyl)-1,1-dimethylurea) or simazine (2-chlor-4,6-bis(ethylamino)-s-triazine), above recommended rates can decrease the subsequent vigour and yield of young apple trees (Hogue and Neilsen, 1988). It is best to be alert to this possibility by knowing the history of previous weed control at a prospective planting site.

These examples show that it is useful to investigate the implications of previous land use at a site prior to making the decision to replant.

11.3 Site Preparation

There are a number of actions that can be undertaken to improve the suitability of a site for orchard establishment. However, the cost of such activities needs to be accounted for when deciding where to plant.

11.3.1 Tillage

Normally, tillage operations are undertaken to about a 20 cm depth in orchards prior to planting in order to produce desirable conditions for the growth of the planted trees. Successful tillage may act to maintain soil infiltration capacity and aeration, to mix pre-plant amendments and fertilizer throughout the main rooting zone and to control weeds. Increasingly, less emphasis is placed upon tillage for the purpose of weed control, in part because of possible detrimental effects on soil structure, but also because of the effectiveness of weed control via herbicides.

Sometimes mechanical manipulation of soils 15–25 cm below the normal tillage depth is warranted. These activities, also referred to as deep ploughing, chiselling, subsoiling or ripping, are intended to break up any compacted or impermeable layers within the root range of young trees. This should increase infiltration and pore size for drainage and water storage, allowing improved root growth and leaching of excess water and salts. The effectiveness of the procedure varies with soil moisture content at the time of ripping, being more effectively performed on dry soils. It is physically much easier to plant into soils after deep ripping. However, ripping as a general preplant orchard practice is probably not justified, as limited growth improvements may not warrant the added expense. Even on soils and for other crops where deep ripping is more commonly undertaken, increases in growth or yield or improvements in soil physical properties have been inconsistent, sometimes temporary and frequently disappointing (Wild, 1988).

11.3.2 Landscape modification

11.3.2.1 Levelling

After clearing the land of previous vegetation or old orchard trees, it may be useful and relatively inexpensive to level an irregular surface. Thus surface drainage depressions may be infilled and a flatter field established for operation of orchard equipment and irrigation systems. (With the advent of pressure-compensating emitters, slope requirements are less exacting for modern low-pressure irrigation systems.) The degree of levelling depends upon the original land surface. Large gulleys have been successfully infilled to create larger contiguous areas of level land. However, problems can arise, since planted apples frequently grow poorly on exposed subsoils or new fill, which can have poor fertility or structure. Pre-plant land modification can be expensive but has been successfully applied prior to planting. For example, the 'Tatura' soil management system involves pushing topsoil into ridges in order to increase soil depth and improve drainage within the tree row when shallow top soils overlie compact subsoils (Baxter, 1977). Similarly, in south-eastern USA, subsoils have been reshaped and levelled with removed topsoil being respread to create a new soil surface with constant topsoil depth.

11.3.2.2 Contouring

Where water runoff and soil erosion concerns are great, orchards can be established parallel to contours, so that orchard operations can be undertaken as nearly as practical on the contour (Plate 11.4). Such planting systems were originally designed so that tillage operations could be undertaken across the slope gradient, reducing the velocity and erosive power of overland flow. The decline in orchard cultivation following the advent of herbicides has greatly lessened tillage operations in orchards. However, planting orchards on the contour allows orchardists to subsequently establish strip cropping systems, where vegetation-free, in-row herbicide strips alternate with between-

row ground-cover strips, which reduce water runoff and soil erosion.

11.3.2.3 Terracing

Terracing is usually considered an extreme form of land shaping. Although practised for thousands of years in many parts of the world to conserve moisture and reduce erosion, establishment costs are high. The procedure involves the construction of broad benches across the steep slopes (usually 20–30°) of rolling land. Such practices are usually considered only when other soil-conservation methods are ineffective. Construction details are contained in many standard soil- and water-engineering texts (Schwab *et al.*, 1966). A variation of the complete terracing method is the construction of a single diversion embankment up-slope of an orchard in humid climates to prevent slope runoff water from flooding orchard land.

11.3.2.4 Drainage modification

The benefits of improved soil drainage can allow successful production of apples on soils and in locations where waterlogging and poor aeration would normally limit the development of orchards. For example, much apple production in The Netherlands has proceeded on appropriately drained land with previously poor drainage. Costs can be relatively high, including the expense of materials, drain installation and engineering design. However, there is considerable information available relating to the depth of installation, spacing, size and type of drains, as well as design and layout procedures from standard soil-engineering texts (Schwab *et al.*, 1966) and, in many regions, from companies specializing in soil drainage.

11.3.3 pH adjustment

If soil pH is not optimum for apple tree growth, the best time to correct the problem is prior to tree planting when ameliorative amendments can be easily worked into the soil without concern for damaging the newly planted trees.

Excessively low pH values are more commonly encountered and are corrected via lime applications. There are a range of suitable liming materials whose ability by weight to neutralize acidity varies and is often expressed as a percentage of pure calcium carbonate (defined as 100%) (Table 11.2).

Limes are usually comprised primarily of calcium compounds but are applied to neutralize acidity rather than for their direct contribution to the calcium nutrition of apple trees. Magnesium-containing limes, such as dolomite, should be considered when soil magnesium contents are low and cultivars such as 'McIntosh' are being planted that are susceptible to the development of magnesium deficiency in heavy crop years. Some liming materials, such as calcium oxide or calcium hydroxide, neutralize acidity more rapidly. These materials can be difficult to apply, since calcium oxide can form larger, less soluble granules after absorption of water from the soil. Calcium hydroxide can be difficult to spread as a fine powder, especially on windy days. Sometimes, inexpensive, locally available sources of liming material, including marl, basic slag, fly ash and packing-house lime, are available to the orchardist. Their relatively cheap cost must be balanced by consideration of their effectiveness, actual

neutralizing ability and possibility of contamination with toxic elements. Packing-house lime (originally calcium hydroxide) can be an economical source of locally available liming material, but probably requires regrinding to achieve effectiveness, since it often forms large insoluble granules after absorbing water and carbon dioxide.

Lime is most effective when finely ground because its reaction rate depends on its surface area in contact with the soil. The reaction is also speeded by intimate contact with the soil, which may be achieved by ploughing and discing the soils after surface applications. Little change in bulk soil acidity was measurable several years after rotavating coarse fragments of packing-house lime into the soil profile. Without incorporation, penetration of even finely ground lime can be exceedingly slow, as indicated by significant pH changes only being detected in the surface 10 cm 5 years after application at 6 t ha⁻¹ of calcium hydroxide to the soil surface without incorporation (Neilsen *et al.*, 1981; Fig. 11.7).

The amount of lime to apply varies primarily with the texture and the organic-matter content of the soil. It is usually calculated as the amount required to achieve target pH values to a fixed soil depth (usually 20 cm) by equilibrating a representative sample of

Table 11.2. Commonly used liming materials and their neutralizing value (data adapted from Tisdale *et al.*, 1993)

Material	Common name(s)	Molecular weight (g mol ⁻¹)	Neutralizing value ^a (%)
Calcium oxide CaO	Quicklime, unslaked lime, burned lime	56	179
Calcium hydroxide Ca(OH) ₂	Hydrated lime, slaked lime, builder's lime	72	136
Calcium-magnesium carbonate (Ca, Mg)CO ₃	Dolomite	184	109
Calcium carbonate CaCO ₃	Agricultural limestone	100	100
Calcium silicate CaSiO ₃	Basic slag	116	86

^aAs a % of pure calcium carbonate set as 100%. To be equivalent to a given quantity of calcium carbonate, neutralizing values exceeding 100% required proportionately smaller amounts of material

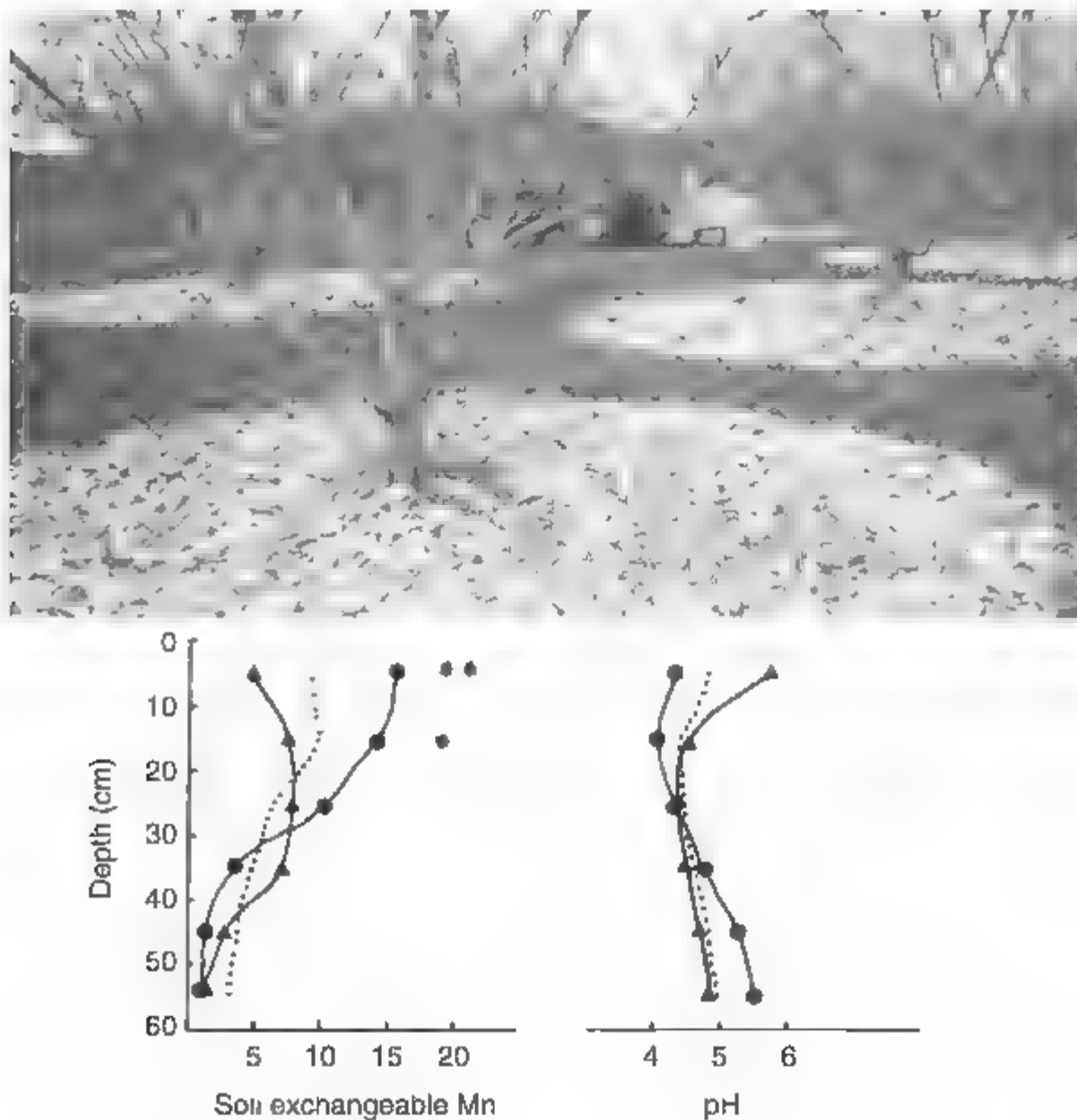


Fig. 11.7. Surface application of various calcium compounds to a 'Spartan' apple orchard in November, 1994, followed by measurements of average soil exchangeable manganese (Mn) and pH with depth for each of the 6000 kg ha⁻¹ Ca(OH)₂ (▲), 12,000 kg ha⁻¹ CaSO₄ (---) and control (●) treatments in 1979. Statistically significant differences indicated at the 0.01 (**) and 0.05 (*) levels.

the soil in a buffer solution. The Shoemaker, McLean and Pratt (SMP) single-buffer procedure has been widely used to make these calculations by many soil-testing laboratories (van Lierop, 1990). When soil pH is uniformly low in an orchard block, a uniform rate of lime can be applied. However, considerable pH variation can occur due to previous management practices, including nitrogen fertilization, irrigation and herbicide use in land previously in orchard. For example, zones of low pH near previous apple tree locations where acid-forming nitrogen fertilizer applications were concentrated have been reported in Washington State orchards (Benson, 1968). In coarse-textured, low-organic-matter, sandy-loam

orchard soils, pH values ranging from 3.9 to 4.4 have been measured in the tree row relative to mid-alley values of 5.4–6.7 (Ross *et al.*, 1985). With the possibility of such large pH differences on old orchard land, it may be appropriate to apply differential, higher rates of lime in old tree rows.

Subsoil pH can be important, since apple roots when planted must begin to proliferate and grow at depths at and below 30 cm. It can be difficult to mechanically incorporate lime effectively to these depths. In regions where very acid subsoils (pH < 5) exist, improved plant growth has been observed several years after incorporation of gypsum, which has acted by reducing soil concentrations of toxic aluminium (Sumner *et al.*, 1986).

There is also some potential to acidify soils with excessively high pH values. For example, the pH of calcareous soils can be reduced by application of acidifying compounds, which also increase the availability of other nutrients by neutralizing calcium carbonate. Acidifying materials include elemental sulphur, sulphuric acid, aluminium sulphate and ammonium polysulphide. Elemental sulphur is often the most effective of soil acidic substances and research on orchard soils has indicated that effectiveness, as with liming, increases with soil incorporation and finer particle sizes (Neilsen *et al.*, 1993). Complete neutralization of calcium carbonate is often too expensive, due to the large quantities of calcium carbonate in many soils. Some success has been achieved by acidifying a portion of the root zone by band application of high rates of acidifying fertilizers, such as ammonium thiosulphates or polyphosphates, after planting. It can be extremely difficult to reduce the pH of saline soils, unless there exists the possibility of leaching large quantities of salt from the soil profile via irrigation. A wiser strategy for such situations may be to avoid planting such sites in the first place.

11.3.4 Other soil amendments

In addition to pre-plant lime and fertilizer applications to improve the performance of a newly planted apple orchard, there are situations where applications of other soil amendments may be advantageous. Recently, the use of various organic amendments and mulches has received renewed attention, due to concerns about the negative impacts that conventional orchard production practices are having on soil quality (Glover *et al.*, 2000). Such applications often depend upon the ready availability of economical sources of suitable organic materials. Locally available sources can reduce transportation costs for such materials, which are often wet and bulky. Source materials may include various hays and straw, grape pomace, manures or sewage biosolids and, increasingly, composted combinations of various of these materials.

The use of organic materials as soil amendments usually involves surface application to the proposed tree row and rotavating to mix materials throughout the root zone prior to planting. Effective application rates are frequently in the 30–60 t ha⁻¹ range since 10–20% by volume of material must be added in order to meaningfully alter bulk soil properties. The nutrients co-applied with the organic materials can improve long-term soil fertility. However, organic materials must be well mixed in the soil to avoid creating excessively saline conditions, since many organics have high salt readings. There may also be difficulties in regulating the nitrogen available to the trees, since applied organics can act to either release or immobilize nitrogen depending upon the carbon:nitrogen ratio of the materials, as well as temperature and moisture conditions in the soil environment.

It is also possible to make applications of these various organic materials to the surface of soils around trees immediately after planting (Fig. 11.8). Such mulch applications offer several benefits, including moderation of soil temperature extremes, conservation of soil moisture, reduction in weed competition, improved nutrient availability (especially phosphorus and potassium) and long-term improvement in the aggregation and permeability of poorly structured soils. A current area of research involves the suppressive effects the addition of organic materials have upon soil-borne pathogens, including *Phytophthora* root rot of apples. An important concern in many regions is that mulches can provide an excellent habitat for orchard voles (mice). These animals can devastate an apple orchard by girdling the trunk and/or the roots. Where voles are a concern, a vegetation-free strip along the tree row is usually a better choice, as it tends to discourage rather than encourage orchard mice.

Effective use of organic materials as amendments or mulches to improve short-term apple tree vigour and production are not guaranteed but are more likely on sites with coarse-textured, low-organic-matter, shallow soils where otherwise limiting nutrient and water stresses may occur.



Fig. 11.8. Black plastic, lucerne and paper mulches in a high-density 'Spartan' apple orchard in autumn 1998.

11.4 Replant-site Preparation

An important consideration when replanting a site where apples have previously grown is the possibility of inhibited growth of the newly planted apple trees, which has been observed in most major apple-growing areas and attributed to the consequence of growing the same crop repeatedly on the same soil. It is likely that the occurrence of such problems will increase as more planting occurs on land previously in orchard and as planting systems are established with the intention of more frequent renewal with new cultivars. Poor growth of apples on replant sites is sometimes referred to as specific apple-replant disease (SARD) but is not always specific, having been observed on sites not previously having apples (Sewell, 1979). Several causal factors have been identified, including a wide range of pathogenic organisms, such as various species of actinomycetes (Otto *et al.*, 1994), fungi and nematodes (Yadava and Doud, 1980). Despite the identification of numerous

individual biotic factors, there is no consensus across all fruit-growing regions concerning the most important single factor or whether several factors act simultaneously or sequentially or interact with adverse environmental conditions to weaken growth of replanted apple trees.

11.4.1 Fumigation

Application of broad-spectrum chemical biocides to old orchard soils prior to replanting has, however, often been effective in improving the initial growth and subsequent yield of replanted apples, despite uncertainty concerning the exact causal factor(s). For example, large yield increases were observed for 'Royal Gala' apple on M7a rootstock after replant application of Metham-sodium at various rates in Washington State. Improved growth has also been reported after use of other general fumigants in various fruit-growing regions (Table 11.3). Local research is probably the most valuable guide to effective fumigation, due to the apparently site-specific nature of the problem in different regions.

Several general practices, however, apply to effective fumigation, including: good site preparation, which usually means removal of old trees and stumps, with as many roots as possible; mitigation of other soil limitations via application of required fertilizers, lime or other soil amendments, followed by ploughing, discing and deep ripping of soil, as appropriate; and application of the fumigant to warm (10–18°C) and moist soil. These latter conditions often occur in either spring or autumn. Fumigation in the autumn has the advantage of dissipation of the fumigant from the soil prior to the planting of young trees. Spring fumigation can be carried out, but caution is required, since soil containing residual fumigant can damage young trees. The dissipation of fumigants from the soil is affected by temperature, being more rapid on warm soils. A germination test can be carried out to determine whether all fumigant has dissipated from the root zone prior to planting in the spring. This test compares the germination of seeds of either cress, lettuce or radish applied to the surface of fumigated

Table 11.3. Fumigation treatments successfully used to overcome replant problems in old orchard soils

Compound	Effective field application rate	Considerations
Chloropicrin (trichloromethane)	25–50 ml m ⁻²	Commercial application recommended due to high toxicity; apply within proposed row, seal with plastic; similarly effective 3–18°C
Formalin (formaldehyde)	400–600 ml m ⁻² , apply with 2–4 l m ⁻² of water	Apply to moist soils with water
Vapam (Metham-sodium) (sodium <i>N</i> -methyldithio- carbamate)	90 ml m ⁻²	Apply to wet soil; can be applied with irrigation water
Basamid (98% dazomet) (tetra-hydro-3,5-dimethyl-1,3,5- thiadiazine-2-thione)	30–50 g m ⁻²	Granular, releases toxic gas upon soil contact; requires incorporation to target depth; seal with water, preferably plastic

and untreated samples of the moist soil sealed in small glass jars and placed in warm, sunny conditions. The test can be repeated at 2-day intervals until germination occurs and the date of tree planting can be established.

The use of broad-spectrum fumigants is non-discriminatory and can decrease populations of potentially beneficial microorganisms, such as vesicular arbuscular mycorrhizae, which have a role in the uptake of plant nutrients such as phosphorus. This may be the reason why the application of relatively high rates of phosphorus, especially in the mono- and diammonium phosphate forms, within the tree planting hole in fumigated, pasteurized or fungicide-treated soils has ensured vigorous growth of young apple trees in old orchard soil (Slykhuis and Li, 1985; Neilsen and Yorston, 1991).

Not all soils will respond to fumigation and, in some apple-growing areas, a seedling bioassay to test for the presence of apple-replant disease has been developed and is offered by some soil-testing laboratories. Tests usually involve comparisons of the growth of apple seedlings in untreated or fumigated soils after 12–14 weeks' growth in pots under greenhouse conditions. Fumigation is recommended when large growth increases (> 150%) are measured for seedlings grown in treated soil (Sewell *et al.*, 1988). Seedling bioassay tests can thus provide valuable information on whether to fumigate or not.

11.4.2 Alternatives to fumigation

Fumigation can be expensive, difficult to accomplish safely and detrimental to beneficial soil microorganisms, such as mycorrhizae. Consequently, environmentally benign alternatives are being continuously sought, although none has yet achieved the wide-ranging success associated with fumigation. For example, planting of marigold (*Tagetes patula* L.) as a cover crop has suppressed root-lesion nematodes (*Pratylenchus* spp.) in New York, where nematodes have been judged an important component of the replant-disease problem (Merwin and Stiles, 1989). Similarly promising suppressions in the American dagger nematode (*Xiphinema americanum*) populations have been observed after planting certain *Brassica* plants (Halbrendt and Jing, 1994).

Replacement of disease-infested soil with new soil in the planting hole is possible, but it can be difficult to locate sufficient high-quality replacement soil and long-term results can be disappointing, as newly planted trees soon grow into the original soil. First-year tree growth has, however, been increased on replant sites by planting hole amendments involving applications of non-orchard soil (Peryea and Covey, 1989) and various organic mixes, often in association with high rates of monoammonium phosphate fertilizer (Neilsen *et al.*, 1994).

11.5 Orchard Planning

11.5.1 Cultivar selection

Projections for the world apple situation indicate that growers will continue to face a period during which production will exceed demand (see also Chapter 2). Cultivar selection is one of the most critical decisions made as new orchards are planned. Although many factors must be considered in selecting cultivars, the planned marketing strategy is of utmost importance. In this section, we shall introduce the subject of cultivar selection; more detailed coverage is presented in Chapters 2, 4, 11 and 24.

11.5.1.1 Wholesale fresh market

Today, a typical supermarket in the USA will display 12–15 different cultivars of apples, several of which are of relatively recent introduction. Growers are scrambling to find the newest cultivar for which they hope to get the early peak price usually received as a successful new cultivar first comes on the market. Unfortunately, in the rush to 'get there first', growers sometimes plant relatively untested cultivars, which prove to be unprofitable because of poor adaptation to their climate, serious cultural problems or lack of sufficient production for the cultivar to be accepted in the wholesale market. Given its many facets, cultivar selection remains one of the most vexing issues facing the fresh-market apple grower.

11.5.1.2 Processing market

In the processing market, the cultivar picture is much more stable than in the wholesale fresh market. For utilization as tinned or frozen apple slices or apple sauce, specific cultivars are preferred and a premium price is paid for them. Although the cultivars of choice vary with locality, the market is relatively stable. Unfortunately, however, the depression of prices related to overproduction and worldwide competition is of concern, particularly with the apple-juice market (see Chapters 2 and 24).

11.5.1.3 Organic apples

The production of organically grown apples has expanded in recent years, but although this trend continues, the organic part of the industry remains a very small part of the total (see Chapter 22).

11.5.1.4 Direct marketing/pick your own

The grower who is able to market fruit directly to the consumer through one of many types of retail outlets or a pick-your-own operation has a real advantage. The wholesale grower has essentially no contact with the ultimate consumer, but rather must deal with the whims of a chain-store buyer. In contrast, in a direct marketing operation, it is quite feasible to 'educate' the customer by offering samples and thereby to sell more and different cultivars. It is not unusual for a direct-market grower to offer 30–40 cultivars, often including old or 'heritage' cultivars, particularly those of a regional nature, which are not available in grocery stores.

11.5.2 Rootstock selection

In sharp contrast to growers of other tree fruits, apple growers are very fortunate in having a wide array of dwarfing rootstocks available (see Chapter 5). The major factors that have an impact on rootstock selection include: vigour, precocity, yield, yield efficiency, disease and insect resistance, anchorage, fruit size and quality, suckering and, last but not least, grower experience and management skills.

11.5.2.1 Vigour

There is ample evidence that, in the early years of an orchard, yield per unit area is largely dependent on the number of trees per hectare (see Chapter 15). This consideration is one of the driving forces in the movement to increasingly dwarfing rootstocks and intensive training systems. The key to successful orchard design is to plant trees close enough to obtain good early yields while avoiding future tree-management problems and not sacrificing fruit yield and/or quality as the trees mature.

The wide range of rootstock vigour available to today's apple grower is nothing less than remarkable. For example, in the 10-year NC-140 rootstock trial, completed in 1989 (NC-140, 1991), tree size, as indicated by trunk cross-sectional area (TCA), varied by a factor of about 17 – from 10 cm² for trees on M.27EMLA to 172 cm² for trees on MAC.24 (Fig. 11.9)

11.5.2.2 Precocity

A very notable characteristic of the dwarf rootstocks is their remarkable ability to induce precocity in scion cultivars. In fact, it is often a concern that such trees tend to flower excessively in the first year or two following establishment in the orchard. The potential problem is the tendency for some rootstocks, such as Mark, to 'runt out' (essentially stop vegetative growth) as a result of excessively heavy fruiting in the second or third year.

11.5.2.3 Yield

The interest in high-density orchards has been driven by the desire for early returns on the orchard investment, and dwarfing rootstocks are mandatory for their precocity as well as their vigour control. In a study in

British Columbia (Quamme *et al.*, 1997), the two high-density systems outyielded the lower-density systems by three to five times over the first 4 years. It must also be realized, however, that, compared with traditional low-density orchards, intensive orchards have higher establishment costs and require greater management skills.

As the young orchard develops, overall canopy volume continues to be the overriding factor influencing yields (Plate 11.5). For this reason, training systems that encourage early canopy development tend to maximize yields. For example, in the NC-140 orchard systems trial, trees trained to the vertical axis had higher early yields per tree and per hectare than trees trained as either a slender spindle or a central leader (Barritt *et al.*, 1997b). Part of this difference is probably due to the minimal pruning of the vertical axis compared with the other two systems.

11.5.2.4 Yield efficiency

Yield efficiency is calculated by dividing the weight of fruit produced per tree by the TCA. In essence, yield efficiency is the ratio of fruit production to wood production. In general, dwarf rootstocks have considerably higher yield efficiencies than the more vigor-

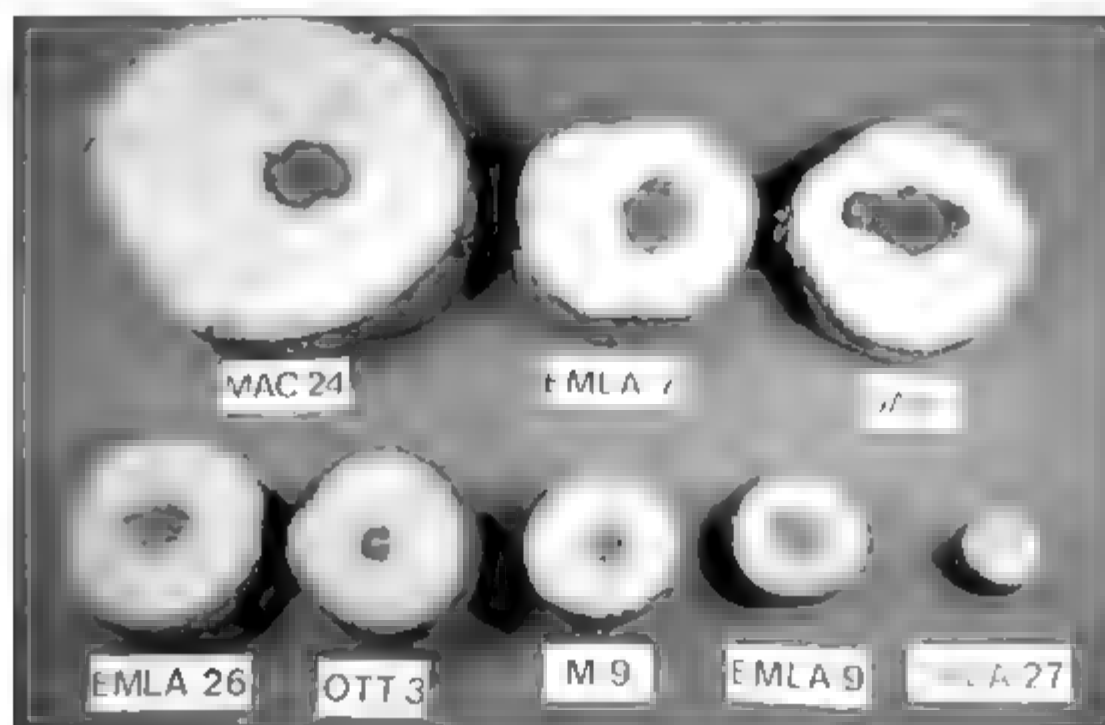


Fig. 11.9. Cross-sections of trunks of 10-year-old 'Starkspur Supreme Delicious' on rootstocks ranging from the vigorous MAC.24 to the very dwarfing M.27EMLA.

ous rootstocks. There is, however, a point of diminishing returns where the tree produces so much fruit and so little wood that tree canopy size is seriously restricted. Thus, the allocated space is not fully occupied and the yield per hectare does not meet expectations. For example, in some trials, trees on Mark have had very high yield efficiencies, but have produced such small canopies that total yields per tree and per hectare are often lower than for trees on M.9.

11.5.2.5 Disease and insect resistance

In making a rootstock selection, disease susceptibility is an important consideration, because of the tremendous impact that certain diseases can have (see Chapter 18). Whole blocks of trees can be devastated by a major outbreak of fire blight (*Erwinia amylovora* (Burrill) Winslow *et al.*). Unfortunately, almost all of the dwarfing rootstocks being planted are highly susceptible to fire blight, as are many of the newer scion cultivars. A fruit grower needs to be particularly alert when both the scion and rootstock are highly fire blight-susceptible and extra care must be devoted to minimizing the likelihood of an outbreak. Viruses and soil-borne fungi can also be troublesome. There is little in the way of insect resistance in apple rootstocks (see Chapter 19). A particularly well-known exception to this statement is the resistance to woolly apple aphids (WAA), which was incorporated in the Malling Merton rootstocks by English researchers who crossed Malling rootstocks with 'Northern Spy', which has excellent WAA resistance.

11.5.2.6 Anchorage

Among the rootstocks available today there is the complete spectrum from those that are completely self-supporting (MM.111) through to those that have a tendency to lean (M.7) and to those for which trunk support is mandatory (M.9). This categorization is based on whether or not the rootstock is able to support the fully fruiting tree in an upright position without additional support (see Chapter 5).

11.5.2.7 Fruit size, maturity and quality

Over the past 20 years, several researchers have evaluated the influence of apple rootstocks on apple maturity, size, quality and storage life. Although differences in fruit size have not always been consistent, trees on OAR1, P.1 and M.27 have tended to produce smaller fruit than trees on M.9, M.26 and B.9 (NC-140, 1991; Barritt *et al.*, 1997a). Fortunately, none of the three that are prone to produce small-sized fruit are among those being widely planted. Rootstock effects on maturity, quality and storage life have been relatively small in studies over multiple sites and years and therefore need not be a major concern in making rootstock choices (Autio *et al.*, 1991).

11.5.2.8 Suckering

With most apple rootstocks in use today, suckering has not been a serious concern. One notable exception is the semi-dwarf M.7, which is well known to sucker more than others. When numerous, there is the obvious labour cost for annual removal, but there is an additional concern when the rootstock is highly susceptible to fire blight.

11.5.2.9 Grower experience/management skills

Most growers have been making the transition from orchards on seedling rootstocks at 100 trees ha⁻¹ to those on semi-dwarfing rootstocks at 300–450 trees ha⁻¹. It is much easier to go to a high-density orchard of 1000–1500 trees ha⁻¹ from a semi-dwarf orchard of 450 trees ha⁻¹ than from a conventional orchard of 100 trees ha⁻¹.

As new rootstock candidates become available, growers should test them in their own orchards, but relatively untested rootstocks should be planted only in small numbers until their suitability is established. Unfortunately, new rootstocks are sometimes made available to commercial growers almost as soon as they are available to researchers. It takes a minimum of 5–10 years to assess the strengths and weaknesses of new rootstocks. In the meantime, the

planting of 'known quantities', such as one of the M.9 clones, is a better choice.

A mistake made by some growers has been to take information from a different part of the country or world and to attempt to duplicate a particular orchard design and system on their own site without considering the differences in soil, climate and management skills. For example, a particular tree spacing in a northern climate, such as western New York or Michigan, may be much too close in the mid-Atlantic area, where tree vigour is notably greater. This has become apparent in data from regional trials, such as the NC-140 rootstock trials, over the past two decades (NC-140, 1991; 1996), which show that, in general, trees in areas with longer growing seasons tend to be larger.

11.5.3 Row orientation

Since the advent of hedgerow plantings, researchers have sought to ascertain the ideal way to orientate rows to maximize the interception of light. Factors that interact and therefore complicate this issue include latitude, time of year, time of day, tree height and shape and row spacing. Results from several researchers indicate that, in general, a north-south row orientation provides both better light interception and a more even distribution throughout the tree canopy than an east-west row orientation and is therefore preferred (Cain, 1972; Jackson, 1980).

11.6 Tree Establishment

11.6.1 Tree quality

In the establishment of a new orchard, tree quality has to be a top priority. An orchard is a long-term commitment and success is, to a sizeable degree, dependent upon the quality of the trees planted. First among the tree-quality attributes has to be trueness to name for both the scion cultivar and the rootstock. There is a tremendous array of both cultivars and rootstocks propagated and sold by nurseries. In recent years the

selection of cultivars and rootstocks has been even further complicated by the explosion of choices of new strains of both scion cultivars and rootstocks. For example, there is a seemingly ever-changing array of strains of 'Gala' and many different clones of M.9 rootstocks. Although individual nurseries tend to concentrate on a limited number of choices, it is not surprising that errors can and do occur. The best insurance against disappointment is to deal with a reputable nursery.

11.6.1.1 Feathered trees

With the trend towards more intensive orchards, productivity in the early years has become critical to economic success. One way to encourage early fruiting is to plant feathered (branched) trees, which can save a year in getting trees into production (see Chapters 6 and 14).

11.6.1.2 Planning

The lack of adequate planning sometimes leads to serious mistakes in buying trees. If a grower decides at the last minute to order trees (for delivery in a matter of weeks or even months), he/she is frequently left with minimal choices of specific cultivar/rootstock combinations. This is particularly true if the combination of choice is in high demand by others. Settling for one's third or fourth choice is very often a serious error in judgement. It is far better to order exactly the cultivar/rootstock desired, preferably 2 years in advance, to ensure its availability. Nurseries often offer a discount for trees ordered well in advance.

11.6.1.3 Tree condition and arrival

Trees must arrive in prime condition and on time. Trees that have either dried out or been frozen during transit should be rejected, because they will probably grow poorly, if at all. Likewise, trees showing signs of either disease infection or insect infestation should be rejected. It is wiser to wait an additional year if suitable replacement trees are not available.

11.6.1.4 Tree storage

When the trees arrive they must be kept dormant and the roots moist. Cold storage is frequently required, but great care must be taken to ensure that the trees are not exposed to ethylene. A cold-storage room either containing apples or in which apples were stored will contain a sufficient concentration of ethylene to kill or severely injure apple trees. The room used to store trees must not contain apples and, if the room has previously stored apples, the atmosphere must be flushed for a lengthy period to minimize ethylene concentration. If suitable refrigerated storage space is unavailable, trees can be 'heeled in' in soil or sawdust on the shaded side of buildings for short-term holding.

11.6.2 Tree planting

11.6.2.1 Season of planting

In regions without excessively cold winters, there are advantages to planting trees in the autumn. Although autumn-planted trees will make no shoot growth until spring, roots will grow when soil temperatures are approximately 5°C or higher. These additional roots can be of considerable value to the tree when shoot growth is initiated in the spring. Drawbacks to autumn planting include lack of tree availability, conflict with harvest, potential damage by voles, rabbits and other wildlife during the winter (Fig. 11.10) and potential winter injury. In irrigated regions, dry soils in the early spring may make it difficult to get good root growth on autumn-planted trees. In areas that experience frequent freezing and thawing cycles, 'frost heaving' can push newly planted trees upwards, exposing the upper roots. Such trees must either be replanted or have soil brought in to cover the roots.

It is well documented in humid areas that trees planted in late winter to early spring grow far better than those planted later in spring. Spring weather is notoriously variable and wet periods that delay planting are frequent. It is critical that trees be available on site so that they can be planted during the earliest suitable weather associated with



Fig. 11.10. A young apple tree that suffered girdling injury from both mice and rabbits. The injury occurred while snow covered the orchard. Mice girdled the base of the tree under the snow and the rabbits, able to travel on an ice coating on the snow, ate bark as high as they could reach. Uninjured bark is apparent in the area in between, which was snow-covered.

appropriate soil conditions. In arid areas, dry soils in the spring may necessitate some delay in spring planting or at least require available water to adequately moisten planting-hole

soil. Whether the trees are planted in autumn or spring, there must be adequate, but not excessive, soil moisture present at planting and during the ensuing months.

11.6.2.2 *Tree spacing and arrangement*

For many decades, apple trees have been planted closer in the row than between rows, thus they can be said to be in a rectangular design as opposed to trees being planted equidistant in both directions (so-called square design). Under the overall umbrella of rectangular designs are an amazingly broad spectrum of orchard designs, which are described in Chapter 15

11.6.2.3 *Placement of pollenizers*

Almost all cultivars of apple require cross-pollination to set commercial crops, and there have been many different approaches taken to meet these pollination needs. With the widespread utilization of the hedgerow design, a commonly accepted practice is to place pollenizer trees (often flowering crab apples) about every 15 m in each row and to offset the pollenizer trees in adjacent rows. Particularly with very dwarfing rootstocks, no space is allocated to the crab apple pollenizer trees. They are set between adjacent fruiting trees and are trained to a tall cylindrical shape. Since crab apples flower so profusely, the severe pruning that is required does not restrict flowering. Among the advantages of crab apples as pollenizers are their annual flowering without the need of thinning, no mix-up of fruit at harvest and a wide choice of flowering time to match most cultivars. A common practice is to plant two to three different crab apple cultivars to better span the flowering period of the main cultivar. Attention must be paid to selecting crab apple cultivars with resistance or immunity to fire blight.

11.6.2.4 *Planting depth*

In planting apple trees, there has been a progression from doing so by hand with a shovel to the use of augers to drill holes to the use of mechanical tree planters.

Regardless of the technique and equipment used, certain standards must be met. The most critical of these is the location of the bud union. After the tree has settled and the soil in the planting hole has consolidated, the bud union should be 4–6 cm above the soil surface; this means that when initially planted, the bud union should be 6–8 cm above the soil surface. If the union is buried or settles below the soil surface, scion rooting can overwhelm the dwarfing characteristics of the rootstock, leading to excessive tree vigour and tree crowding. If too much rootstock is left exposed above the soil, burr-knots (masses of root initials) may develop. These burr-knots lead to deformed trunks (Fig. 11.11), can serve as entry points for fire blight bacteria and for insects such as the dogwood borer and can also lead to excessive dwarfing. In the 1980s, a recommendation was made that trees be budded higher in the nursery (by 15–20 cm) so that trees could be planted deeper, theoretically offering additional tree support, especially for trees on M7, which tend to lean. Unfortunately, high-budded trees set in clay soils did not thrive (Lyons *et al.*, 1983) and the practice was largely abandoned.

The regulation of planting depth is relatively easy with trees planted by hand, but can be more of a challenge when using a tree planter. It may be necessary to have workers follow behind a tree planter to adjust planting depth of individual trees. Such adjustment is far easier immediately after planting than after the soil has settled around the roots.

11.6.3 *Tree support*

For the last several decades there has been an ever-accelerating trend towards the use of size-controlling rootstocks in new apple orchards; few apple trees are planted today on vigorous seedling or even the relatively vigorous MM.111 rootstocks. Another part of this trend has been a shift to increasingly dwarfing rootstocks. In the opinion of most people, the more dwarfing stocks (M.26 size or smaller) require support because of the inability of such trees to support heavy



Fig. 11.11. The lower trunk of a 10-year-old 'Starkspur Supreme Delicious' on M.26 EMLA. Just below the bud union is a large burr-knot (group of root initials), which has deformed the normal shape of the trunk and is a potential entry point for fire blight bacteria, as well as certain insects, such as the dogwood borer.

crops (see Chapter 15). Support can range from a short post providing only trunk support to 3 m stakes, which are in turn supported by a wire (Fig. 11.12). There are intermediate types of supports, including single posts of metal or wood and wire trellises, as well as elaborate wood and wire or steel and wire trellises. Each has its special attributes and drawbacks and the choice is difficult. The basic question for trees on dwarfing rootstocks is not 'Should the tree be supported?' but rather 'How should the trees be supported?'

One of the greatest concerns with any type of tree support is the relatively high cost, both for the materials and for the labour for installation (Fraser and Oakes, 1999). Because of the

high costs, there is a temptation to seek cheaper approaches by using fewer or smaller posts or by forgoing the wire to support the wooden or metal stakes. When the trees are 1–2 years old and largely vegetative, a minimal support system, such as an unsupported conduit, appears to be sufficient; by the fourth or fifth year, however, it becomes apparent that a minimal system is totally inadequate. As a rule, it is far easier and cheaper to install an adequate support system at the outset, rather than to have to replace an inadequate system that fails when the trees begin to bear heavily. It is very easy to underestimate the amount of stress imposed upon a support system by apple trees that have a full crop, experience a heavy rainfall event and are then buffeted by high winds a few days or even weeks before harvest.

Some growers avoid the necessity for tree support by using severe pruning practices, basically following the procedures recommended for central-leader trees by Heinicke (1975). If the leader is headed by one-half each year, it may be possible to grow trees on a rootstock such as M.26 without support. There are data, however, which show that such severe pruning reduces yields in the early years of the orchard, probably by enough to more than pay for a support, which would avoid the need for such heavy pruning (Barden and Marini, 1998).

11.6.4 Pruning at planting

Prior to the introduction of feathered trees, most apple trees were planted as 'whips', which were unbranched trees ranging in height from about 1.5 to 2 m. Such trees were routinely headed at a height of 70–100 cm. Such heading was to re-establish the balance between the top of the tree and the root system, which had been damaged by being dug and shipped bare-root, as well as to induce buds to break and to produce shoots that would eventually become the lower tier of scaffold limbs.

With the availability of well-feathered trees (multiple branches at the desired height and angles), the need to head the newly planted tree to induce branching was no



Fig. 11.12. Young vertical axis apple trees in southern British Columbia. Individual trees are supported by bamboo poles, which are in turn supported by a wire at approximately 2.5 m.

longer valid. Various recommendations have been made for such trees, including no heading at all if the feathers are acceptable in both number and location. Others suggest heading at 25–30 cm above the top feather. Opinions also vary as to whether the feathers should be headed. The issue here is the balance between the root system and the top of the tree. As discussed above, if trees are planted in the autumn or very early spring, root growth can precede bud break and therefore may meet the water needs of the new growth. If, however, the buds break soon after planting, the tree may suffer from lack of water, will make little or no growth and may even die from desiccation. In the arid north-western apple areas of North America, there is a tendency for shoot growth to slightly precede root growth, which seems to create a sensitivity to water stress if moisture conditions are not optimum. On the basis of the available information, it is our recommendation that the leader and feathers be headed unless the trees were planted in the previous autumn. The goal is to get new orchards into production as soon as possible,

but it must be kept in mind that we must first grow the trees, and good growth during the first year is vital.

11.7 Summary and Conclusions

The establishment of apple orchards involves a great many decisions, each of which has a long-term impact on the success of the operation. Climatic considerations are of paramount importance and encompass both broad geographical and very local factors. Apple trees require approximately 1000 h of chilling during their dormant season and perform best where winters are not extremely cold and summers not excessively hot. The flowers and young fruit of apple are subject to spring-frost injury, so site selection is based to a sizeable degree on this consideration. Locations on the leeward side of lakes or other large bodies of water are excellent because of the temperature-moderating effect of the water. Other preferred sites are those that have good air drainage due to slope or position above the surrounding area.

There are likewise many aspects of soil that are vitally important in choosing a site for an apple orchard. Among the physical characteristics that must be considered are soil texture, structure and depth, because of effects on drainage, nutrient availability, water relations, aeration and equipment travel. Because of slow movement in the soil, lime to adjust soil pH as well as applications of phosphorus and potassium should be made prior to planting so that they may be ploughed down into the root zone. Other potentially useful procedures may include breaking up impermeable layers in the soil, levelling, contouring, terracing, improving drainage or adding additional soil amendments. In situations where a replant problem exists, there may be a need for fumigation; efforts are under way to develop more environmentally benign alternatives.

The planning of a new orchard should start at least 2 years prior to planting to allow the ordering of the desired cultivar/rootstock combination(s). There is an increasingly broad list of potential cultivars, and they vary not only with the climate but with the market to be served. Likewise, there are many rootstocks from which to choose, but the worldwide trend is towards increasingly dwarfing rootstocks. Whatever the choice of cultivar and rootstock, the trees should come from a reputable nursery, be planted as early as possible in the spring and be supplied with adequate moisture. There are many options as to tree spacing and arrangement, initial pruning, tree support and training systems. Regardless of the cultivar, rootstock and orchard system selected, the success of the orchard will depend to a large degree on the characteristics of the site on which it is planted.

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12 Nutritional Requirements of Apple

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12.1 Nutrient Requirements

In common with many plants, apple trees require 16 elements for successful completion of their life cycle. Among these elements are carbon, hydrogen and oxygen, which are important non-mineral elements and major constituents of organic materials. Mineral elements contained in high (%) con-

centrations within the plant include nitrogen, phosphorus, sulphur, potassium, calcium and magnesium. Minerals usually comprising lower (p.p.m.) concentrations include iron, manganese, copper, zinc, boron, molybdenum and chlorine. It is difficult to calculate the total nutrient requirements for apple trees, since it is necessary to account for nutrients contained in the peren-

nial framework of the trunk and roots as well as those contained in leaves, new shoots and roots, which are produced annually. Some measurements have been undertaken for the major nutrients in high-yielding orchards and expressed per unit of land area (Table 12.1). These estimates indicate that the annual requirements (for leaves and fruit) are lower than nutrient requirements for many annual crops. Planting density can further alter orchard nutrient demand. For example, unit-area potassium requirements were greater in more densely planted 'Golden Delicious' orchards cited in Table 12.1 because of the higher yield of fruit (which has a high potassium concentration). Few nutrient estimates are available for 'super-spindle' plantings, which can have tree densities in excess of 4000 trees ha⁻¹ and usually have even higher fruit yields from a greater number of small trees per unit land area.

12.2 Direct Determination Of Apple-tree Nutrient Status

In orchards, direct determination of leaf nutrient concentration has most frequently been used as a routine method of monitoring and adjusting the nutritional status of apple trees. Recently, with increased concerns for

fruit quality, some emphasis has been placed upon use of fruit nutrient concentrations (especially calcium) to optimize the harvest and storage quality of fruit.

12.2.1 Leaf nutrient concentration

Leaf nutrient concentration reflects the factors influencing nutrient availability, including those affecting nutrient supply from the soil, and year-to-year variation in climate and crop load. Nutrient concentration is not stable within the season, as the rate of nutrient supply and internal tree cycling alters throughout the period of annual leaf and shoot development. Some nutrient concentrations decrease (e.g. nitrogen, phosphorus, potassium and zinc), while others, such as calcium and manganese, increase over the growing season (Fig. 12.1). As a consequence, a standard sampling time is used when annual concentration changes are minimal for most nutrients. Generally this period occurs 110–125 days post full bloom, which coincides with the middle of the growing season.

Since considerable variation in leaf nutrient concentration can be measured among various types of leaves and even leaf positions within a tree and among trees within an orchard block, standard sampling proce-

Table 12.1. Distribution of major nutrients in apple orchards

Nutrient kg ha ⁻¹	'Delicious' ^a (30 years old, 124 trees ha ⁻¹ , 44.8 t fruit ha ⁻¹)	'Golden Delicious' ^b (14 years old, 500 trees ha ⁻¹ , estimated 90 t fruit ha ⁻¹)				
	Whole tree	Top framework	Leaf	Roots	Fruit crop	Whole tree
Nitrogen	110.5	39.7	32.6	27.6	21.3	121.2
Phosphorus	17.8	6.0	3.9	5.6	4.0	19.5
Potassium	141.7	33.9	25.7	16.8	120.0	196.4
Calcium	167.7	83.5	53.5	21.0	4.4	162.4
Magnesium	25.4	8.0	6.7	3.5	3.7	21.9
Sulphur	—	8.5	2.8	3.9	0.2	15.4
Chlorine	—	4.5	24.3	1.3	15.2	45.3

^aAs adapted from Batjer *et al.* (1952); whole-tree values include blossoms, fruitlets and prunings removed from the tree.

^bAs adapted from Haynes and Goh (1980); leaf measurements at leaf fall; framework and root measurements in dormant season.

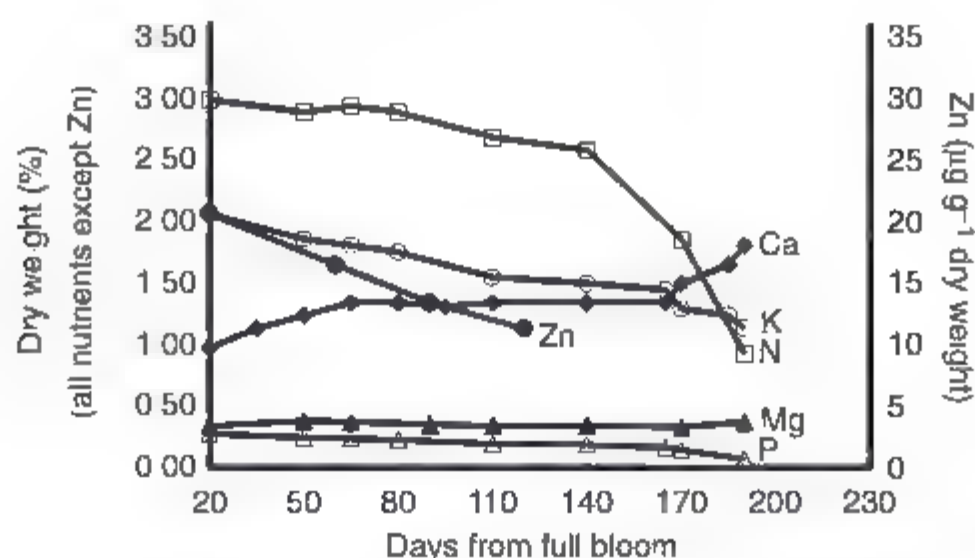


Fig. 12.1. Seasonal trends of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and zinc (Zn) concentration of mid-terminal, new-year extension-growth leaves for 'Delicious' apple: data from Rogers *et al.*, 1953, except for Zn data from Nielsen, 1988).

dures are usually prescribed to obtain consistent and representative samples. Samples commonly comprise 25–50 leaves collected from 20–25 randomly selected trees from the same cultivar/rootstock combination, with leaves collected around the tree from the mid-shoot portion of the current season's extension growth on shoots of representative vigour (Fig. 12.2).

Care is usually taken to select leaves free of insect, disease and mechanical damage, with surfaces uncontaminated by chemical residues. Standard leaf values are usually compiled for heavily cropping trees, since light crops, such as those resulting from biennial bearing, differentially affect leaf nutrient concentration, decreasing, for example, leaf calcium while increasing leaf potas-



Fig. 12.2. Typical mid-terminal, new-year extension leaves suitable for mid-season sampling.

sium. Considerable practical advice concerning the preparation and chemical analysis of collected samples is available from publications concerned with tissue testing (Jones, 1998). Critical leaf nutrient standards applicable for apple are available (Table 12.2). Under ideal conditions, such standards would be developed for each apple cultivar and climatic condition, since there are important genetic and environmental factors affecting nutrient uptake and requirements and the expression of deficiency. Nevertheless, these values provide general guidelines for assessing the nutritional status of apple.

A different approach to interpreting leaf nutrient concentrations is the diagnosis and recommendation integrated system (DRIS), which is based upon comparing nutrient ratios between sample plants and a high-yielding subgroup (Beverly, 1991). This method purports to be less affected by time of sampling and to rank nutrients in order of their limitations to growth. Experience with orchard crops, especially apple, has been

limited (Righetti *et al.*, 1990) and DRIS frequently provides no more information than the use of critical values.

12.2.2 Fruit nutrient concentrations

In some fruit-growing regions, fruit mineral analysis, especially for calcium, is used as an aid in postharvest management decisions (e.g. Perring, 1984). As with leaf values, individual fruit nutrient concentrations vary considerably. As illustrated for nitrogen and calcium, there are major differences in nutrient concentrations among cultivars and years and within the season (Fig. 12.3). Furthermore, within- and between-tree variation, often associated with variation in size of individual apples, frequently necessitates sampling large numbers of fruit (25–50) in order to obtain values representative of the crop. Fruit nutrient concentrations have been expressed on a fresh weight basis after wet digestion or on a dry-weight basis after ashing freeze-dried samples. It is also important

Table 12.2. Critical leaf and fruit nutrient concentrations for apple

Nutrient	Unit	Deficiency ^a	Normal	Toxicity
Leaf				
Nitrogen	% DW	< 1.5	1.7–2.5	
Phosphorus	% DW	< 0.13	0.15–0.30	
Potassium	% DW	< 1	1.5–2.5	
Calcium	% DW	< 0.7	1.2–2.0	
Magnesium	% DW	< 0.20	0.26–0.36	
Sulphur	% DW	< 0.1	0.1–0.3	
Manganese	p.p.m. DW	< 25	25–120	> 120
Iron	p.p.m. DW	< 45 (?) ^b	45–500	
Boron	p.p.m. DW	< 20	20–60	> 70
Copper	p.p.m. DW	< 5	5–12	
Zinc	p.p.m. DW	< 14	15–120	130–160
Molybdenum	p.p.m. DW	< 0.05	0.1–0.2	
Fruit (harvest)^c				
Nitrogen	mg 100 g ⁻¹ FW		50–70	
Phosphorus	mg 100 g ⁻¹ FW	7–9 ^d	> 11	
Calcium	mg 100 g ⁻¹ FW	< 4	> 5	
Boron	mg 100 g ⁻¹ FW	< 0.8		

^aSeverely deficient leaves can sometimes have unexpectedly higher leaf concentrations

^bLeaf iron concentrations not correlated with iron deficiency

^cWhole-fruit concentrations minus stems and seeds.

^dAppropriate for cultivars susceptible to low-temperature breakdown.

DW, dry weight; FW, fresh weight.

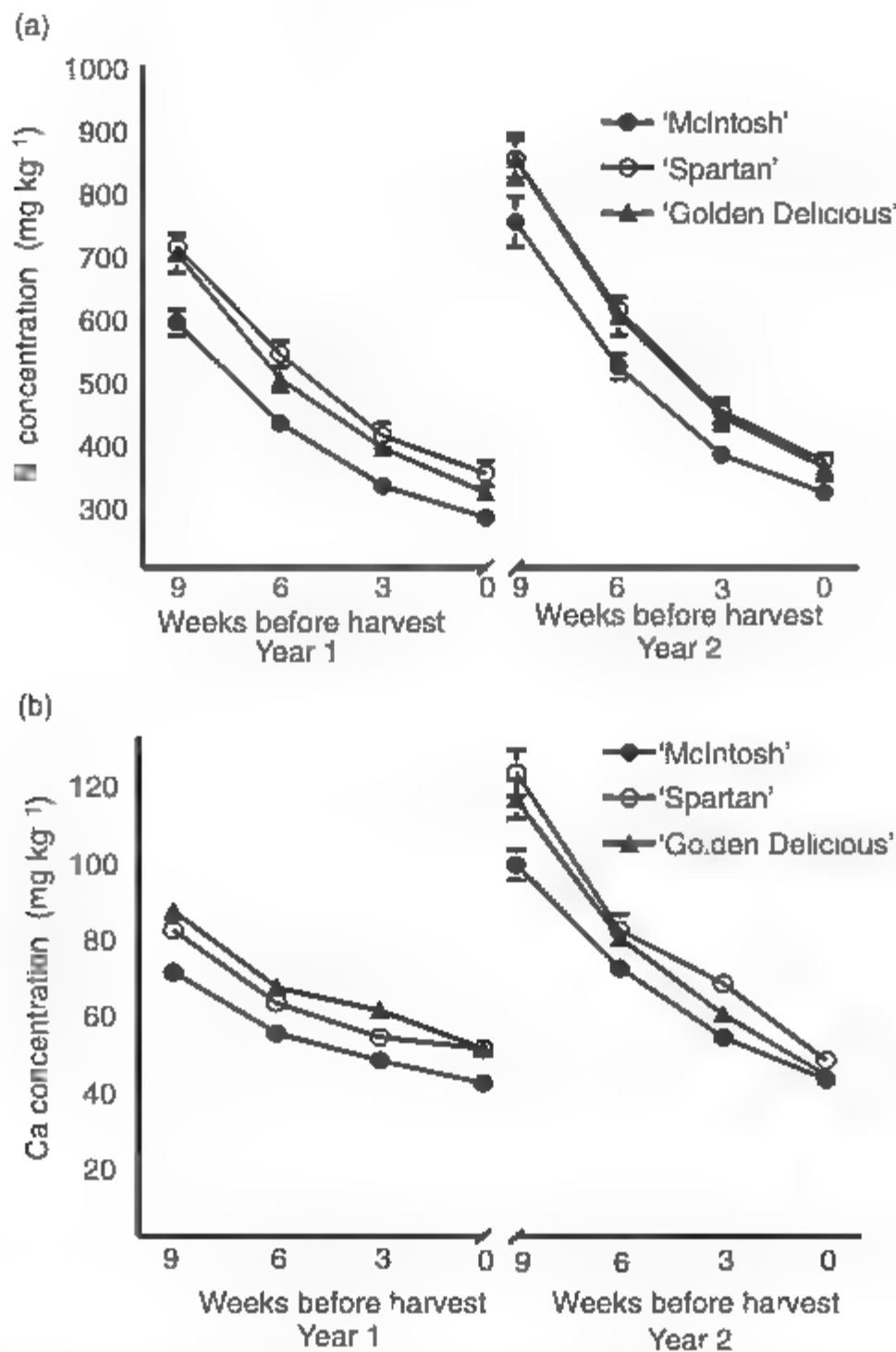


Fig. 12.3. Seasonal trend in (a) fruit nitrogen (N) and (b) fruit calcium (Ca) a fresh-weight concentration as affected by cultivar in successive years. Average of data from 30 commercial orchards in the Pacific north-west. Vertical bars represent mean value ± 1 standard error when larger than symbol. (Adapted from Wolk *et al.*, 1998)

to consider the part of the fruit that has been analysed, since values are reported for whole fruit (usually without seeds), skin, cortical plugs, opposite sectors and so on. Nutrient gradients occur from skin to core and from calyx to stem end of fruits and nutrient redistribution can occur postharvest. Faust *et al.* (1967) indicated patterns that differ by nutrient for apple fruit. Some critical values proposed for whole apple fruits are indicated in Table 12.2, although it is likely that such values are less universally applicable than critical leaf nutrient concentrations.

12.3 Nutritional Implications of Rooting Characteristics

The root system plays a major role in the absorption and translocation of water and nutrients from the soil throughout the tree. Apple cultivars are usually grafted on clonal rootstocks, which have been selected on the basis of characteristics such as precocity, ability to reduce scion vigour and resistance to pests, rather than ability to take up water and nutrients (Chapter 5). Nevertheless, apple root systems have several general

characteristics that affect their nutrition and response to soil conditions.

The distribution and effectiveness of fruit tree roots, including apple, have been comprehensively reviewed by Atkinson (1980). Apple root systems have been mapped after relatively labour-intensive excavations (Fig. 12.4). Roots are often non-uniformly distributed within the exploitable soil volume, can sometimes penetrate to depths exceeding

1.2 m and, without competition from other trees, can achieve a lateral spread exceeding that of the top branches. Despite the potential for extending great distances and depths, apple root density is low, frequently orders of magnitude less than that of *Graminaceae* species, with which apple is often interplanted (Fig. 12.5). This implies a more limited exploitation of the soil volume than might otherwise be expected.

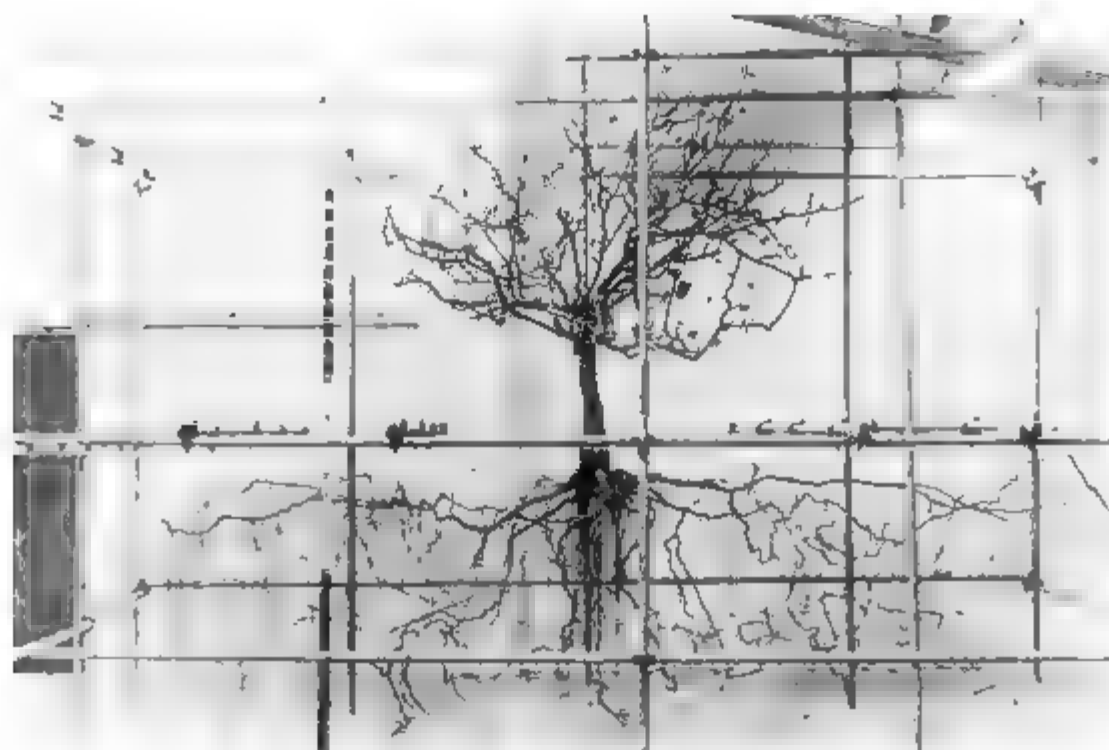


Fig. 12.4. Excavated whole apple tree on vigorous rootstock, East Malling Research Station (photo courtesy D. Atkinson)

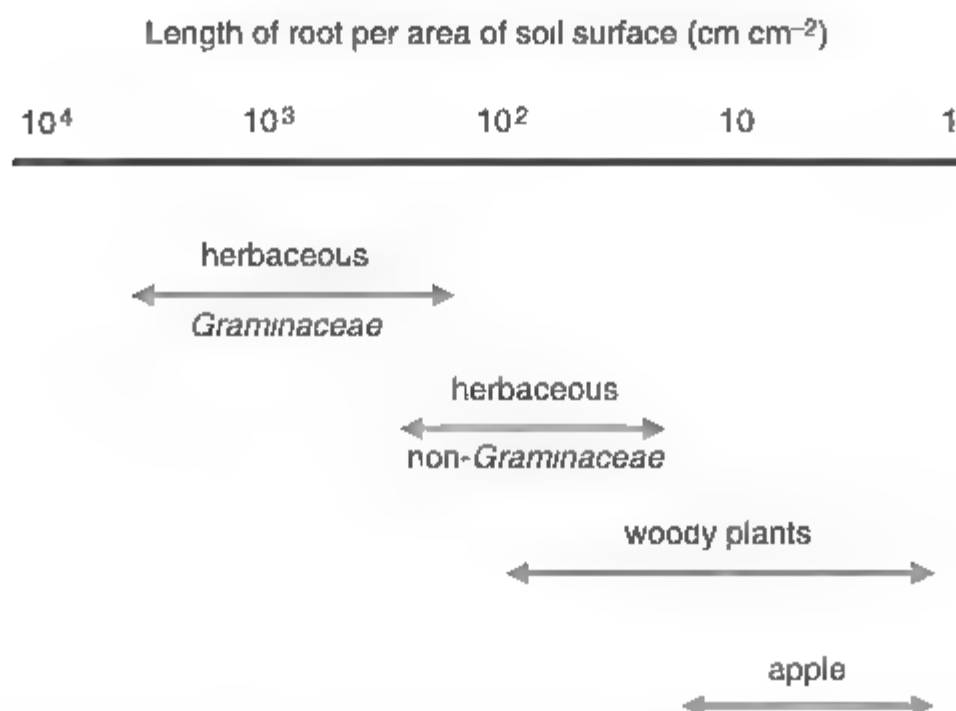


Fig. 12.5. Typical range of root length, expressed as cm cm^{-2} of soil surface for various species, including apple

There is also considerable plasticity in the growth of apple root systems. For example, roots proliferate when nutrient and water conditions are favourable, as beneath drip emitters through which nutrients are applied. In loamy sand soils, average root location, after 5 years of nitrogen and phosphorus fertigation through drip emitters, was within 30 cm of the soil surface and emitter location for 'McIntosh' apple trees on M.26 and M.9 rootstocks (Fig. 12.6). The pattern was less pronounced for the more vigorous M.7 rootstock. Atkinson (1980) also indicates that planting density influences root distribution, with roots deeper and more laterally restricted when trees are planted more closely together.

Nutrient uptake by roots occurs by direct root interception, by mass flow of dissolved nutrients in water absorbed by the plant and by diffusion if a concentration gradient for the specific ion develops round the absorbing root (Fig. 12.7). For an annual maize crop (*Zea mays* L.) growing in a fertile soil, the principal pathways have been calculated for key nutrients (Table 12.3) and they indicate that dominant pathways differ for nutrients. Apple is likely to access fewer nutrients by direct interception due to lower root density and because, in general, apple trees are grown in low fertility soils. Nevertheless, the relative importance of the pathways is probably pertinent for apple and the consequences for availability of nutrients in orchard soils is subsequently discussed for each nutrient.

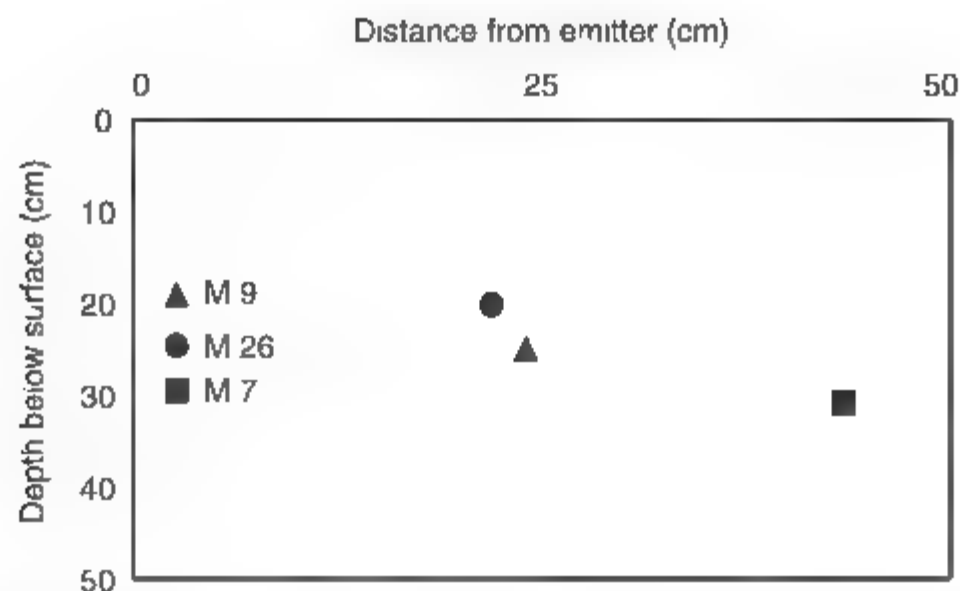


Fig. 12.6. Average depth below surface and distance from a drip emitter for all roots of 'McIntosh' apple as affected by rootstock. Trees maintained for five growing seasons under daily drip irrigation with annual N + P fertigation

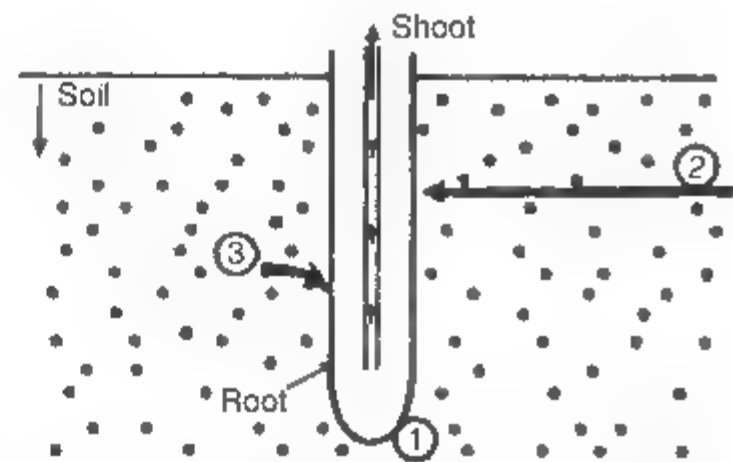


Fig. 12.7. Major pathways of nutrient acquisition by plant roots: 1, root interception; 2, mass flow of water; 3, diffusion (adapted from Barber, 1984).

12.4 Soil Testing

Less reliance is placed upon soil testing to determine the nutritional status of apple orchards. Difficulties associated with the meaningful use of soil tests for perennial crops such as apple are greater than for annuals. It is difficult to collect a representative sample from the rooting zone of a crop that is both deeply and sparsely rooted. Also, localization of roots, as induced by fertilizer and water additions, may disproportionately increase the importance of a small portion of the soil profile. Critical soil values are not easily established for apple, which potentially has a longer period of nutrient uptake than annuals and also has the capacity of storing and recycling some nutrients within a perennial root and top framework.

Table 12.3. Principal method of nutrient adsorption for maize (adapted from Barber, 1984).

Adsorption method/nutrient	Amount of nutrient required (kg ha ⁻¹)	Proportion (%) of requirement suppl able by		
		Diffusion	Mass flow	Root interception
Primarily by diffusion				
Phosphorus	39	94	6	3
Potassium	196	78	20	2
Primarily by mass flow				
Nitrogen	190	0	99	1
Sulphur	22	0	95	5
Copper	0.1	0	400	10
Boron	0.2	0	350	10
Molybdenum	0.01	0	200	10
Mass flow and root interception				
Calcium	39	0	429	171
Magnesium	45	0	250	38
Manganese	0.3	0	133	33
Mass flow, diffusion and root interception				
Zinc	0.3	33	33	33

Most soil extracts attempt to simultaneously characterize rapidly available soluble and exchangeable nutrients while estimating the quantity of nutrients potentially available from inorganic and organic soil components. The usefulness of these values varies with their ability to simulate the soil chemical conditions that control the availability of a nutrient and so predict the uptake of nutrients by the crop. This is likely to vary with the individual chemistry of nutrients as discussed in the following sections describing soil availability for each nutrient. There have also been insufficient long-term fertilization trials for apple to calibrate annual responses to modified soil nutrient levels. Important changes in crop load and soil moisture regimes, for example, can modify responses in successive years.

Despite these limitations, soil testing can be a useful indicator of the relative nutrient status of orchards, especially when monitoring changes over time. Furthermore, it is the only way to determine possible nutrient limitations prior to orchard establishment (Chapter 11). Several important soil characteristics, including soil pH and salinity, can be readily measured. Soil pH has an important effect on the availability of nutrients to

plants, as detailed for individual nutrients later in this chapter. Soil salinity is important because apple trees, like most fruit crops, are sensitive to excess salinity. Methods of dealing with suboptimum pH and salinity conditions are discussed in Chapter 11.

12.5 Augmenting Apple Nutrition

12.5.1 Soil applications

In apple orchards, fertilizers are applied directly to the soil to raise nutrient levels if they are inadequate for the successful growth of the crop. They are also applied to maintain soil fertility, which will decline if nutrient removal from the soil, via processes such as crop uptake (Table 12.1), leaching, volatilization or denitrification, exceeds nutrients added via weathering of minerals and the mineralization of organic matter.

12.5.1.1 Solid fertilizer additions

Nitrogen is the most frequently deficient and most commonly applied fertilizer in orchards. Addition to the soil of phosphorus

and potassium is warranted when soil-test results, plant response or tissue analysis indicate a need. Calcium additions can be large when lime is applied to increase soil pH. Sometimes magnesium and boron applications are recommended, while most other micronutrients are rarely applied via the soil. Additional details concerning effective soil application of various nutrients are discussed further in the orchard-management section for each nutrient.

Placement of solid fertilizers, particularly the more insoluble forms such as phosphorus and potassium, is very convenient prior to orchard establishment because of the ability to readily incorporate broadcast fertilizer. Soluble fertilizers, especially nitrogen, can be broadcast on the orchard surface and readily carried into the root zone with precipitation or irrigation. Placement, as concentrated within the herbicide strip, may be important in order to reduce competitive uptake from orchard-floor vegetation. Banding of essential fertilizer is less frequently undertaken in established orchards, despite a potential for more effective uptake of such fertilizers in soils of low fertility. Application of high rates

of mono-ammonium phosphate fertilizers within the planting hole is an example of band application in orchards, which can successfully stimulate initial tree root growth, providing the salinity created by concentrating the soluble fertilizer is not excessive.

An important environmental effect of fertilization is the acidifying tendency of common orchard fertilizers (Table 12.4) resulting from the conversion of ammonium to nitrate-nitrogen in the soil.

12.5.1.2 Soluble fertilizer additions (fertigation)

The addition of fertilizers with irrigation water (often referred to as fertigation) is a newer technique for fertilizing apple trees. Fertigation has several advantages, including the ability to transport soluble nutrients directly to the root zone whenever water is applied to the plant. In this way, fertilizer amounts and timing can be precise and adjusted to coincide more closely with actual plant demand, without the necessity of frequent traffic throughout the orchard to broadcast fertilizer. The method works best

Table 12.4. Equivalent acidity of commonly applied fertilizers and suitability for fertigation (adapted from Tisdale *et al.*, 1993)

Fertilizer	Content	Equivalent acidity (kg CaCO ₃ per 100 kg fertilizer to neutralize)	Fertigated
Nitrogen			
Ammonium nitrate	33–34% N	62	Yes
Ammonium sulphate	21% N, 24% S	110	Yes, acidity concerns
Urea	45–46% N	71	Yes
Calcium nitrate	15.5% N	–20	Yes
Potassium nitrate	13–14% N, 44–46% K ₂ O	–26	Yes
Phosphorus			
Phosphoric acid	52–54% P ₂ O ₅	110	Yes, acidity concerns
Mono-ammonium phosphate	11% N, 48% P ₂ O ₅	58	No
Di-ammonium phosphate	16–18% N, 46–48% P ₂ O ₅	70	No
Triple super phosphate	45–46% P ₂ O ₅ , 1% S	Neutral	No
Potassium			
Potassium chloride	60–62% K ₂ O	Neutral	Yes
Potassium sulphate	22% K ₂ O, 22% S	Neutral	No

with low-pressure micro-irrigation systems, including drip, microjet and minisprinkler, which tend to concentrate roots in smaller soil volumes due to localized water additions. This, in turn, increases tree reliance on a smaller soil volume, creating a necessity to maintain optimum soil conditions in this important zone. Declining pH can be a serious problem, especially when acidifying fertilizers are repeatedly applied to poorly buffered soils. The advantages of targeting nutrient additions directly to the root zone and the concentrating effects on root distribution are not observed when fertigation occurs via sprinkler systems, which apply water over the whole orchard floor.

Only readily soluble fertilizers (Table 12.4) can be fertigated after inclusion via an injector or siphon into the irrigation system (Fig. 12.8). Fertilization can thus be adjusted by irrigation zone but not to suit individual trees. Comparative studies between broadcast and fertigated application of nitrogen usually emphasize the ability to achieve similar yield, growth or nitrogen uptake at lower nitrogen rates when fertigating (Nielsen *et al.*, 1999). Effective scheduling of irrigation to avoid over-application of water (as discussed later in this chapter for nitrogen) offers the potential to reduce leaching of fertigated nitrogen to the groundwater, since nitrogen moves with water.

The mobility of phosphorus and potassium is much greater when fertigated, increasing the ability to apply these nutrients rapidly when required. Experience with fertigating micronutrients is quite limited. Although chelates or sulphates of most minor elements are sufficiently soluble to fertigate, these nutrients, if required, are most efficiently supplied via foliar sprays. Incomplete understanding of the seasonal variation in nutrient demand by apple currently limits growers from taking maximum advantage of the flexibility of fertigation timing. The attractiveness of fertigation will increase as knowledge of tree nutrient demand improves. Additional information regarding the fertigation of various nutrients as part of an orchard nutrient-management strategy is discussed separately for individual nutrients.

Details regarding the principles and practices of fertigation are beyond the scope of this chapter but are available in several recent reviews (Haynes, 1985; Bar-Yosef, 1999). Since optimum water application is critical to correct delivery of fertigated nutrients, much valuable information can also be obtained from standard irrigation manuals and texts, such as that prepared for drip irrigation by Dasberg and Bresler (1985).

12.5.2 Foliar applications

Nutrients can be directly supplied to apple trees via spray application of dilute concentrations of minerals to foliage, buds and even bark. The quantity of nutrients capable of being absorbed through waxy outer



Fig. 12.8. Fertigation headworks for addition of soluble fertilizer directly into the irrigation system

cell layers is often small relative to tree nutrient demand. Nevertheless, for apple, timely application of several nutrients via sprays has improved tree growth and yield by amelioration of deficiency symptoms (as for micronutrients) but has also improved fruit quality (as for calcium and phosphorus) by reduction of physiological disorders of fruit (Table 12.5). The mechanisms of nutrient uptake and factors improving absorption of foliar-applied nutrients have been detailed in a review by Swietlik and Faust (1984). The relative importance of foliar application as a source of supply of individual nutrients when managing orchard nutrition is subsequently discussed for each nutrient.

12.6 Special Nutrient Considerations

12.6.1 Organic production

There is increasing interest in organic apple production, as discussed in Chapter 22. Such an orientation can alter nutritional practices since allowable fertilizer products are regulated by an organic certification body. Although there can be some variation in acceptability of products among groups, in general, use of synthetic fertilizers is often not allowed and there is a greater emphasis on maintenance of soil organic matter via use of organic composts, mulches and green manures (Edwards, 1998). Thus nitrogen, for example, is not applied as a fertilizer such as

Table 12.5. Timing, rate and concentration of major individual mineral nutrient sprays successfully applied to apple

Nutrient	Common form	Usual timing	Rate ^a (kg ha ⁻¹)	Spray concentration (g 100 l ⁻¹)
Major nutrients				
Nitrogen	Urea	To foliage to correct deficiency, including postharvest to maintain cropping	2–11	200–1000
Magnesium	Epsom salts (MgSO ₄ ·7H ₂ O), Mg(NO ₃) ₂	To early-season foliage (during extension growth) to correct deficiency	45–90	1200–2000
Phosphorus	KH ₂ PO ₄	To early-season foliage and fruit to reduce low-temperature breakdown	22.5–45 22	500–600 1000
Calcium	CaCl ₂	To fruit, usually mid- to late season to reduce disorders such as bitter-pit and improve quality	14–21	300–500
	Ca(NO ₃) ₂		23–34	600
Micronutrients				
Boron	Solubor	Before pink and to foliage, including postharvest to maintain yield and correct deficiency	2.8–5.6	60–100
Zinc	ZnSO ₄ (36% solid)	Late dormant (silver tip to bud swell) as maintenance or to correct deficiency	4.5–45	120–1200
	ZnSO ₄ (liquid form, 47 g Zn l ⁻¹), Zn chelates, Zn oxides	To foliage to correct deficiency, maintain levels	18.9–100 l	250–3000 ml l ⁻¹
			Manufacturer's label guidelines	
Iron	Fe chelates	To foliage to correct deficiency	1.1–2.25	Label guidelines
Manganese	MnSO ₄	To foliage to correct deficiency	2–9	60–200
Copper	Copper oxysulphate, copper oxychloride	To early-season foliage of non-fruiting trees; late dormant (green tip) in fruiting trees	1–2 1–2	50 200

^aHigher rates may be required when deficiency is severe and multiple applications may also be required.

ammonium nitrate but rather as an appropriate organic source with lower nitrogen content, which is slowly released after mineralization of nitrogen-containing organic compounds. Acceptable nitrogen sources might include, for example, fish fertilizers, blood meal or various composted organics, providing they do not contain prohibited constituents, such as sewage biosolids. Similarly acceptable sources of phosphorus may include suitable composts and rock phosphate, while potassium might be applied via composts, wood ashes or a mined but not synthesized mineral, such as potassium sulphate. Similar restrictions and recommendations exist for most mineral supplements, including addition of amendments to adjust soil pH. Orchardists contemplating organic production should be aware of the regulations appropriate to their region and be prepared for the additional emphasis on the long-term maintenance of soil fertility.

12.6.2 Integrated fruit production

Recently there has been a trend in commercial fruit production towards optimization of apple growth and quality while safeguarding the environment and human health. This is often referred to as integrated fruit production (IFP) (see Chapter 21) and also has implications concerning orchard nutritional practices. Some issues, such as maintenance or improvement in orchard soil fertility and organic-matter content, parallel the concerns of organic production. There is a further desire to control nutrient and water-supply to minimize effects on the environment. This is likely to mean increased chemical analysis of orchard soil, leaf and fruit samples to target precisely nutrient application to demand. Avoiding excessive water application will also reduce nitrate contamination of groundwater. Fertigation has been suggested as more appropriate to IFP, since nutrient application rates can be reduced and timing matched to tree nutrient demand. It is likely that further implications for nutrient management will emerge as practices of IFP evolve.

12.7 Individual Nutrients

12.7.1 Nitrogen

Nitrogen is a highly mobile nutrient that cycles between the atmosphere, the soil, living organisms and ground- and surface water (Fig. 12.9). It is the nutrient that is most often applied to apple trees and in the largest amounts and, consequently, has been the most studied.

12.7.1.1 Soil availability

Inorganic nitrogen is taken up by tree roots as either ammonium or nitrate. To a lesser extent, apple roots are also capable of absorbing organic nitrogen compounds, including urea, glutamate and aspartate. The availability of soil nitrogen for plant growth is dependent on both organic and inorganic soil properties and on factors determining microbial activity. The majority of nitrogen taken up by the plant is as nitrate (Mengel and Kirkby, 1982), which occurs naturally in soil solutions in much higher concentrations (up to 200 p.p.m.) than ammonium (~1 p.p.m.), and this relationship persists even when soils have been amended with ammonium fertilizer (Fig. 12.10). In soils, nitrate is unbuffered – that is, it is present almost entirely in solution; thus the majority of nitrate moves to the tree root in mass flow, although localized diffusion gradients may arise when depletion zones develop around roots. In contrast, ammonium is adsorbed to the soil cation-exchange complex and can also be fixed within the lattices of certain 2:1 layer clay minerals, such as illite and vermiculite, often competing with potassium for such sites. Movement of ammonium to the root is by both mass flow and diffusion.

The concentration of nitrate within the soil solution is governed by the microbial mineralization of organic matter and the conversion of ammonium to nitrate (nitrification), nitrate uptake by microorganisms and plants and nitrate leaching by water from precipitation or irrigation (Fig. 12.9). Additions of nitrogen to the soil occur by microbial fixation of N_2 from the atmosphere, dissolved in precipitation, or by inor-

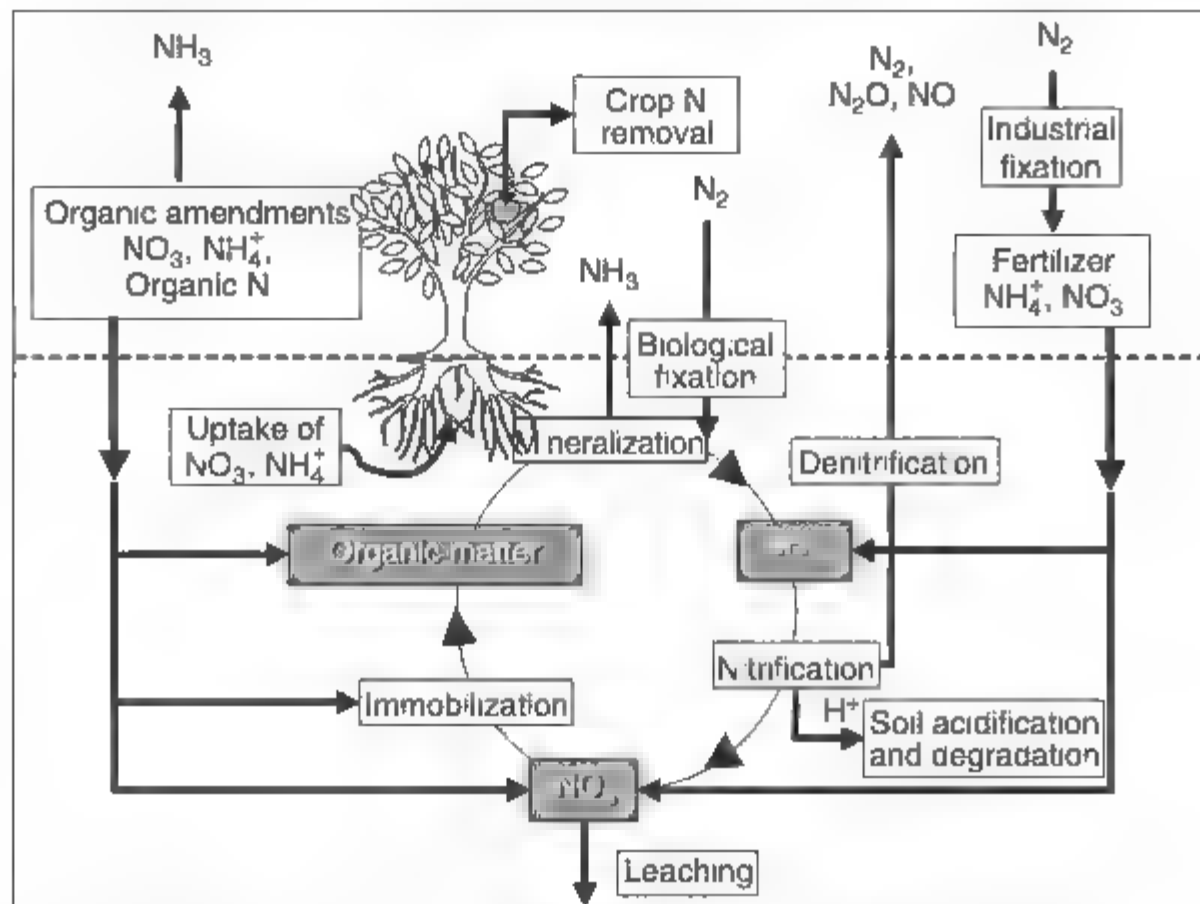


Fig. 12.9. Potential cycling of nitrogen in a typical apple orchard.

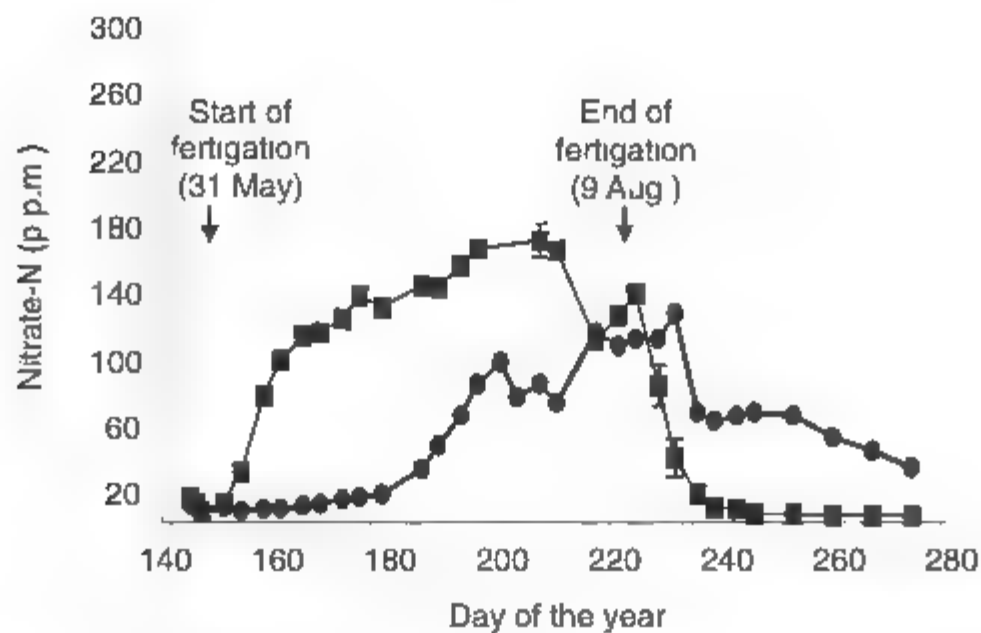


Fig. 12.10. Change in soil solution nitrate-N concentration at 30 cm depth beneath drip emitters in response to daily fertigation (31 May–9 Aug.) of 30 g N as either ammonium sulphate (●) or calcium nitrate (■). Vertical bars represent mean value ± 1 standard error.

ganic fertilizer and organic amendments. As a consequence, the concentration and availability of nitrate in the soil solution vary considerably throughout the growing season. Factors that affect microbial activity, such as temperature, carbon source, oxygen and water-supply, all have a bearing on the

availability of nitrogen for growth. For example, the nitrification of ammonium did not occur immediately on addition of ammonium sulphate to orchard soils (Fig. 12.10) but was probably suppressed by low soil temperatures and incorporation into soil organic matter.

Nitrogen additions as organic amendments or fertilizer can have several detrimental effects on the environment. The high mobility of nitrate results in losses to groundwater, particularly in well-drained soils receiving either high levels of precipitation or irrigation. Soil application of ammonium- or urea-based fertilizers may result in acidification as a result of nitrification (Table 12.4), particularly in poorly buffered soils. Gaseous losses of ammonia to the atmosphere are most likely to occur when ammonium-based fertilizers are surface-applied to high-pH soils, whereas denitrification is most likely in waterlogged situations where soils are poorly drained.

Because the state of soil nitrogen is so dynamic, limited use has been made of soil tests to determine availability. Extractions with 2 M KCl have been used to determine both nitrate and ammonium levels in soils. Weinbaum *et al.* (1992) point out that, despite the difficulties associated with assessing potential nitrogen mineralization in tree root zones and the inherent variability in root and soil nitrate distribution, high residual nitrate levels in orchard soils should be heeded as a signal to reduce fertilizer inputs. Changes in soil-solution nitrate and ammonium concentrations over time and in response to both fertilizer and water inputs can also be monitored through soil suction lysimeters. Sampling of soil solu-

tion in a soil receiving spring-broadcast fertilizer and sprinkler irrigation (Fig. 12.11) indicated that availability of broadcast fertilizer may be limited by rapid leaching of applied nitrogen out of the root zone. Similar effects might be expected if a broadcast fertilizer application is followed by a heavy rainfall.

12.7.1.2 Tree nitrogen demands

It has long been recognized that tree fruits have a requirement for nitrogen that may be greater than that supplied by the soil. Increased vegetative growth responses of apple trees were demonstrated by Lyon *et al.* (1923) and increased bloom by Bradford (1924) in proportion to additions of fertilizer nitrogen. Plant nitrogen is a major constituent of amino acids, proteins, nucleic acids and other compounds and plays a major role in plant metabolic processes. Nitrogen uptake by roots is an active process and is independent of concentration and maximum uptake by apples can occur at very low soil-solution concentrations (~ 0.28 p.p.b.) (Bhat, 1983). Thus, restricted uptake at low soil-solution concentrations is probably the result of an inability to maintain the movement of sufficient nitrogen to the root surface. Nitrate is reduced to ammonium mainly within the roots in apple trees, although movement of

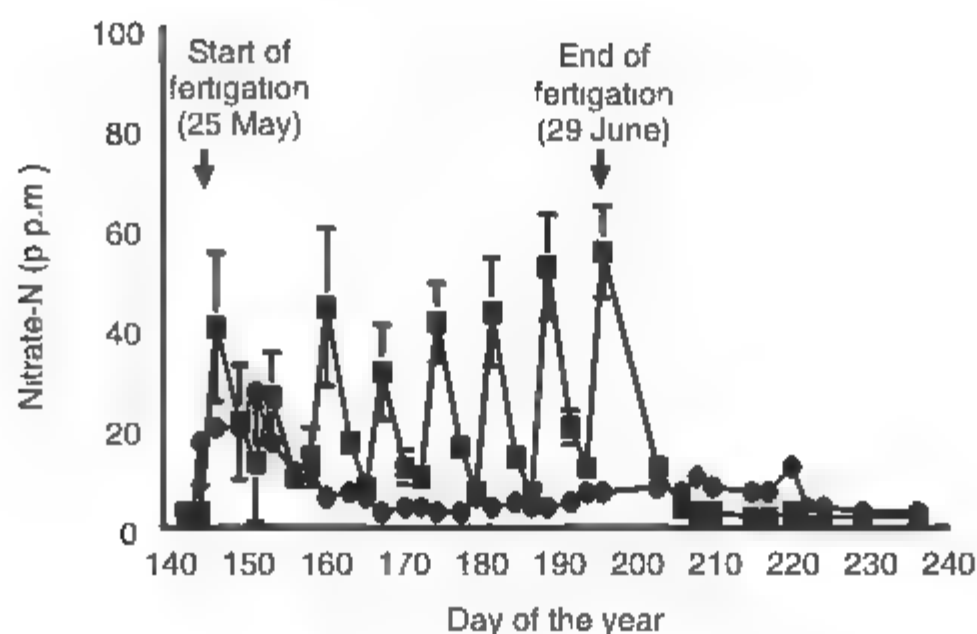


Fig. 12.11. Change in soil solution nitrate-N concentration during the growing season in response to 25 g nitrogen as ammonium nitrate applied either as a single broadcast application on 25 May (●) or as eight fertigations made every 5 days (■) (25 May–29 June). Drip irrigation applied daily. Vertical bars represent mean value ± 1 standard error.

root-supplied nitrate into leaves and subsequent reduction have been reported for apple trees receiving high levels of nitrate fertilizer (Titus and Kang, 1982).

The absolute nitrogen requirements of trees are high compared with other nutrients (Table 12.1). The total nitrogen content of apple trees shows some variation ranging from around 2 g per tree at planting for high-density apple plantings of trees on dwarf rootstocks to up to 890 g per tree for standard 30-year-old trees (Tables 12.1 and 12.6). In modern (high-density) production systems, total tree nitrogen content by year 6 is probably around 30 g per tree (100 kg ha⁻¹).

On an annual basis, nitrogen is required to support the growth of new tissues. The developing leaves and fruit of apple trees are major sinks for nitrogen. In mid-season, it has been estimated that 40% of total tree nitrogen may be found in leaf tissue in standard mature apple trees (Batjer *et al.*, 1952) and 40–50% in leaves of young potted trees (Forshey, 1963). In young dwarf trees, 51% of

total tree nitrogen was found in leaf and fruit tissue, of which 18% could be attributed to fruit (Nielsen *et al.*, 2001b). Attempts have been made to determine the annual demand for nitrogen based on the removal of nitrogen from the orchard. In mature trees (14–21 years), around 25–26 kg nitrogen ha⁻¹ was removed annually in fruit and prunings (Greenham, 1980; Haynes and Goh, 1980).

When the portion of nitrogen annual uptake that is incorporated into the framework of the tree was included, annual removal was estimated as 33 kg ha⁻¹ from 9–12-year-old 'Cox's Orange Pippin'/M.7 (Greenham, 1980) and 52 kg ha⁻¹ from 30-year-old 'Delicious' trees (Batjer *et al.*, 1952). These estimates assume that all fallen leaf tissue is incorporated back into the soil. However, in semiarid areas where orchard floors may be dry, fallen leaves may be blown out of tree rows and thus may not be incorporated back into the tree root zone. Under this assumption nitrogen removal may then include losses from senescent leaves (Table 12.7).

Table 12.6. Total nitrogen content of apple trees.

Tree density (trees ha ⁻¹)	Cultivar	Nitrogen content	
		g per tree	kg ha ⁻¹
3300	'Golden Delicious'/M 9 at planting	2.2	7.4
3300	'Golden Delicious'/M 9 end of year 1 ^a	8.2	27
3300	'Elstar'/M 9 end of year 4 ^b	19.7	65
n/a	M 9/M 9 end of year 5 ^c	15.0	n/a

^aNielsen *et al.* (2001a).

^bNielsen *et al.* (2001b).

^cMason and Whitfield (1960).

n/a, not available

Table 12.7. Estimates of annual nitrogen requirements of dwarf apple trees: nitrogen removal in fruit and senescent leaves

Cultivar	Nitrogen content	
	g per tree	kg ha ⁻¹ ^a
'Golden Delicious'/M 9 end of year 1	2.84	9.4
'Elstar'/M 9 end of year 4	10.21	33.1
'Gala'/M 9 end of year 3	10.49	34.7
'Gala'/M 9 end of year 6	12.19	40.2

^aAssumes tree density of 3330 trees ha⁻¹ in the autumn and that tree rows characteristically have weed-free strips.

Estimates of nitrogen requirements for growth are complicated by plant nitrogen cycling, which occurs both within and between seasons. Extensive reviews of this topic have been previously published (Titus and Kang, 1982; Millard, 1996). Nitrogen assimilated by leaves is stored throughout much of the growing season as leaf protein, but, as with most deciduous trees, some of the stored nitrogen can be mobilized and withdrawn from apple leaves before leaf abscission. The proportion of leaf nitrogen that is withdrawn from apple leaves during senescence has been measured in several studies and ranges from 23 to 50% (Titus and Kang, 1982). The withdrawal of leaf nitrogen may start as early as the cessation of shoot growth or as late as the onset of leaf senes-

cence, but it is likely that the most rapid withdrawal occurs 3–4 weeks before leaf fall. The timing and rate of nitrogen withdrawal probably depend on many factors, including nutrient availability, crop load and environmental conditions. Nitrogen withdrawn from leaves in the autumn is stored in the woody tissues of the tree as proteins or amino acids, which are broken down and are subsequently remobilized to supply nitrogen for the growth of new tissues the following spring. The total amount of tree nitrogen that is involved in remobilization may be quite large. In newly planted 'Golden Delicious'/M.9, over 50% of total tree nitrogen at planting had been cycled out of woody tissues to support new root and shoot growth 70 days later (Fig. 12.12a).

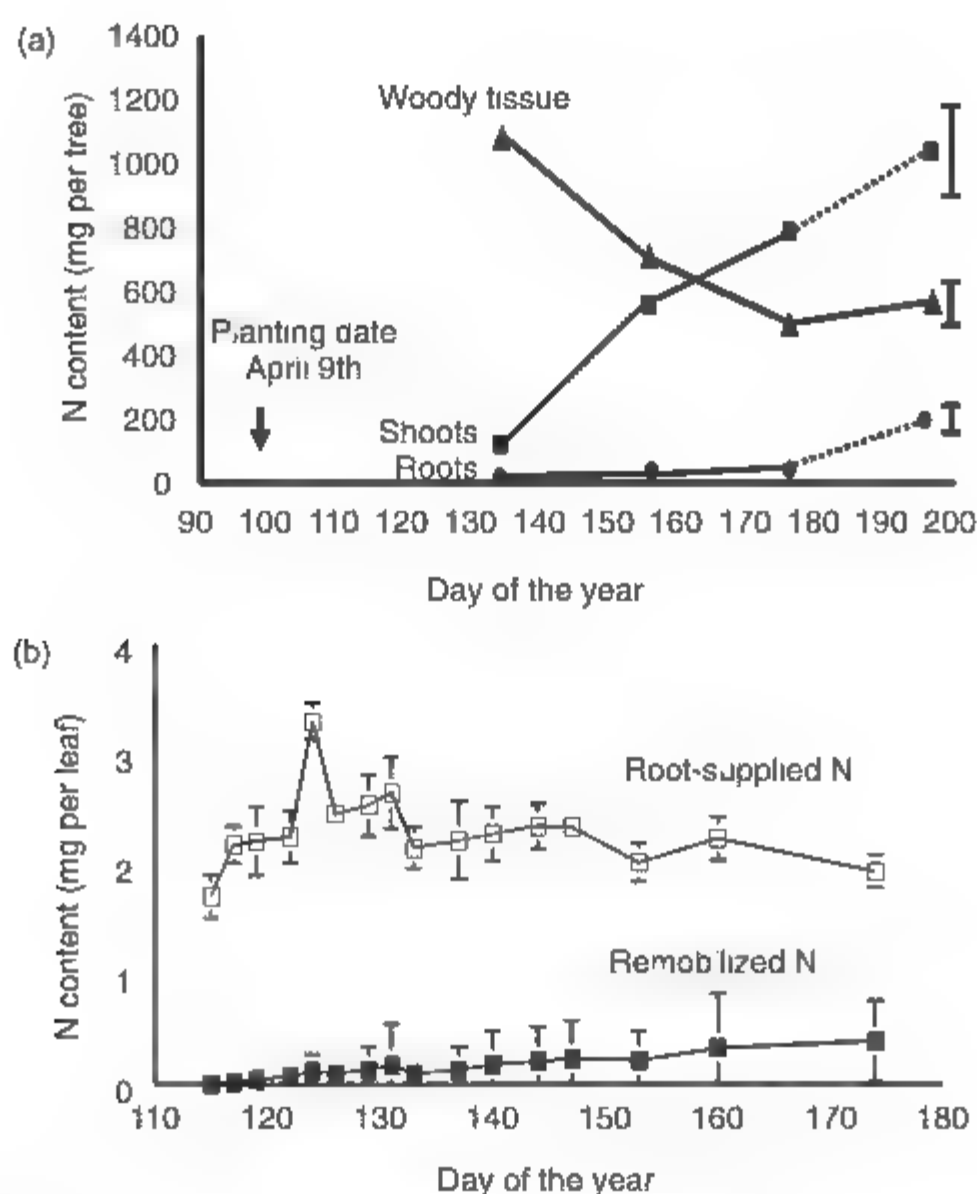


Fig. 12.12. (a) Remobilization of unlabelled nitrogen from woody tissue into new growth in newly planted 'Golden Delicious'/M.9 (dotted lines represent period when unlabelled nitrogen could be from both remobilization and root uptake) (b) Content of root-supplied and remobilized nitrogen (N) in spur leaves of 3-year-old 'Elstar'/M.9. Vertical bars represent mean value ± 1 standard error.

Early spring remobilization of nitrogen is largely independent of current nitrogen supply to the roots (Tromp and Ovaas, 1973; Millard, 1996). In general, evidence suggests that root uptake of nitrogen in the spring does not occur until after remobilization is under way. For 3-year-old 'Elstar'/M.9 trees, the nitrogen content of spur leaves came mainly from remobilization and was present in the leaves before root uptake of nitrogen occurred (Fig. 12.12b). This may be because low soil temperatures in the spring reduce nitrate uptake or because high concentrations of remobilized and cycling amino acids in the roots and/or a lack of necessary carbon skeletons for amino acid synthesis suppress nitrogen uptake. Thus remobilized nitrogen is probably most important to the growth that occurs before the development of the shoot-leaf canopy with its substantial photosynthetic capability. The relative importance of remobilized nitrogen to seasonal growth is dependent on the magnitude of both the nitrogen in storage and that which is currently available. In the absence of root-supplied nitrogen, a strong relationship has been shown between the extent of shoot growth and the amount of stored nitrogen (Harley *et al.*, 1958; Hill-Cottingham and Bollard, 1965). In M.26 apple rootstocks the proportion of nitrogen for leaf growth that was derived from remobilization varied between 18 and 87% for trees receiving high and low supplies of nitrogen in the spring, respectively (Millard and Neilsen, 1989). Remobilized nitrogen contributed 50% of the nitrogen in shoot leaves, 90% of the nitrogen in the spur leaves that subtend the fruit and 60% of the nitrogen in the fruit (Neilsen *et al.*, 2001b). The time when root nitrogen uptake starts to occur is thus probably a function of tree nitrogen status (demand), phenological stage and soil nitrogen availability. Later in the season, the timing of nitrogen supply to the roots can affect partitioning of nitrogen to different tissues. Khemira *et al.* (1998) showed that spring-applied broadcast fertilizer in 9-year-old standard and spur-type 'Delicious'/M7 trees was found in above-ground tissues rather than roots, but that nitrogen from a preharvest broadcast application was allocated preferentially to the roots.

Undersupply of nitrogen leads to poor tree growth and reduced yield due to fewer and smaller fruit. Symptoms of nitrogen deficiency include poor fruit set and early fruit drop, small leaves that are uniformly pale green to yellow, chlorotic basal leaves that abscise prematurely and thin twigs with brown to reddish bark. Diagnosis of tree nitrogen status is often based on measurements of shoot growth and leaf nitrogen concentration in midsummer, with subsequent nitrogen requirement based on a reference range of concentrations where < 1.5% is considered deficient and 1.7–2.5% is considered sufficient (Table 12.2).

In general, oversupply of nitrogen is more of a problem in orchard management than undersupply. In addition to potential leakage to the environment of excess nitrogen that is not taken up by trees, oversupply of nitrogen can lead to excessive vigour and poor fruit-quality characteristics (Faust, 1989). Typical effects may be reduced firmness at harvest and after storage or reduced red colour development when internal ethylene production continues to occur, resulting in fruit that are picked over-mature (Fallahi, 1997). The incidence of several storage disorders, such as cork spot, bitter pit and internal browning and breakdown (Bramlage *et al.*, 1980; Terblanche *et al.*, 1980), has also been linked to excess nitrogen supply. Such detrimental effects of excess nitrogen have been linked to increases in fruit size and shading from vigorously growing shoots, among other factors. Vigorous growth related to nitrogen oversupply has also been linked to increased susceptibility to diseases, such as fire blight (Van der Zwet and Keil, 1979).

12.7.1.3 Orchard nitrogen management

Extensive reviews of orchard nitrogen management and its effect on the environment have been published previously (Weinbaum *et al.*, 1992; Sanchez *et al.*, 1995). Both of these reviews recommend that fertilization rates and management strategies for tree fruits should include a judgement of tree nitrogen status, crop nitrogen demand, soil nitrogen availability and other site-specific variables. Responses to nitrogen fertilizer additions,

such as increased vigour, increased yield, darker leaf colour and higher leaf nitrogen concentration, may only occur with trees of low nitrogen status, as nitrogen uptake is probably restricted in trees of high nitrogen status (Table 12.8). Moreover, leaf nitrogen concentration may be unaffected by increased uptake of nitrogen in response to supply if dilution due to increased leaf growth occurs. Thus, leaf nitrogen concentration as a sole method of diagnosis of nitrogen requirement is not satisfactory, particularly when tree nitrogen status is above deficiency. Estimates of tree nitrogen demand based on removal in the crop and other tissues, as previously described, could be used as a starting-point for fertilizer application rates, modified by consideration of leaf and soil nitrogen concentration.

Compared with many other crops, the annual nitrogen requirement for apple trees is a relatively modest 30–100 kg ha⁻¹. For established trees, there are also numerous reports of adequate growth and cropping without any nitrogen-fertilizer additions on fertile soils (Atkinson, 1980). However, recommended nitrogen application rates may typically range from 75 to 150 kg ha⁻¹ and in some cases even higher. Traditionally, growers have broadcast nitrogen fertilizer in spring and/or autumn. Single-broadcast applications of nitrogen imply that either sufficient nitrogen can be taken up during a restricted period of high nitrogen availability, just after application, or that applied nitrogen becomes incorporated into soil organic matter and is slowly released. However, single-dose, spring fertilizer applications may be inefficient, as uptake in spring can be limited by low demand during

remobilization (Fig. 12.12) and nitrate can be rapidly removed from the root zone when broadcast fertilizer applications are followed by irrigation (Fig. 12.11) or by heavy rainfall. Autumn broadcast applications are also likely to be inefficient, although this would depend on timing with respect to root activity. Applications made in colder regions, where uptake may be limited by temperature and demand, are likely to be susceptible to leaching by either winter rains or snow melt (Tagliavini *et al.*, 1996). The effects of nitrogen on apple cold-hardiness are unclear. Concern is often expressed that late-season applications of nitrogen, which may promote new extension growth, could result in increased susceptibility to winter damage. Conversely, trees with low nitrogen status may also be sufficiently weakened to be susceptible to winter damage. However, there are few published data to either support or refute these statements. Because of the inherent inefficiency in single-dose nitrogen applications, typical application rates of up to 200 kg ha⁻¹ may be four times the tree requirements (Sanchez *et al.*, 1995). More efficient use of nitrogen is likely if broadcast applications are split to match periods of demand. Khemira *et al.* (1998) demonstrated that late-summer broadcast nitrogen applications (preharvest) did not adversely affect current fruit nitrogen concentrations but resulted in root uptake and storage of nitrogen, which was subsequently remobilized for growth in the following season. The amount of nitrogen fertilizer required is also affected by competition from orchard-floor vegetation. Decreases in the amount of broadcast nitrogen required to meet growth requirements have been reported in response to the intro-

Table 12.8. Estimates of fertilizer nitrogen applied in excess of crop nitrogen demand (adapted from Kein *et al.*, 1989, and Weinbaum *et al.*, 1992).

Nitrogen application rate (kg ha ⁻¹)	Leaf nitrogen concentration (%)	Mean annual yield (t ha ⁻¹)	Estimated annual removal in crop (kg ha ⁻¹)	Estimated mean nitrogen excess (kg ha ⁻¹)
50	1.9–2.4	47.7	23.8	26.2
150	2.4–3.2	54.3	27.1	122.8
250	2.5–3.1	45.1	23.0	226.9
400	2.5–3.2	47.1	23.5	376.4

duction of weed-free (herbicide or mulch) strips associated with the tree row (Hogue and Neilsen, 1987)

An alternative method of fertilizer supply is through irrigation water (fertigation), which has been used both where irrigation is mandatory and where it is supplemental. Usually applied through low-pressure microsystems, fertigation of nitrogen offers the possibility of controlling availability both spatially and temporally and potentially improving nitrogen-fertilizer use efficiency. Controlled availability over time is evident from measurements of soil-solution nitrate concentrations in response to daily (Fig. 12.10) and weekly fertilizer applications (Fig. 12.11). Levin *et al.* (1980) suggested that it is appropriate to assume a 50% nitrogen use efficiency for fertigated apple trees. Comparisons of fertigated and broadcast applications of nitrogen on tree growth and yield show, in general, that lower rates of fertigated nitrogen maintain a similar tree nitrogen status to that achieved with higher rates of broadcast nitrogen (Neilsen *et al.*, 1999). Quite low rates of fertigated nitrogen were sufficient to meet tree requirements in The Netherlands (15–20 g per tree) (Kipp, 1992) and the UK (20 g per tree; 26 kg ha⁻¹) (Hipps, 1992) and, in both studies, tree performance was either similar to or better than that of trees receiving broadcast nitrogen at rates of 80–100 g per tree. The rates applied to the fertigated trees in these studies are

much closer than typical broadcast rates to estimates of tree demand (Table 12.7) for high-density apple orchards.

Control of nitrogen losses through leaching may be more achievable in irrigated than in rain-fed orchards, particularly if micro-irrigation systems are used and water applications are scheduled to meet evaporative demand. Under sprinkler irrigation, leaching losses of up to 242 kg ha⁻¹ have been reported for apple trees receiving up to 175 cm rainfall + irrigation per year (Stevenson and Neilsen, 1990). Leaching losses from trees receiving daily drip irrigation were much lower when irrigation was scheduled to meet evaporative demand rather than applied at a fixed rate (Fig. 12.13).

In order to control the timing of nitrogen supply and potentially reduce total inputs and losses to the environment, a considerable amount of work has been undertaken on supplying nitrogen by foliar sprays (Titus and Kang, 1982). Urea is the most common nitrogen form in foliar nutrition (Table 12.5), although calcium and potassium nitrate have also been successfully used. Generally, solution concentrations of urea are 5% or lower. Translocation of summer-applied foliar urea from leaves to other tissues has been variously described as rapid and relatively complete (Boynton, 1954) to limited (Forshey, 1963). Attempts to supply total tree nitrogen by foliar applications have resulted in poor growth, possibly because of poor

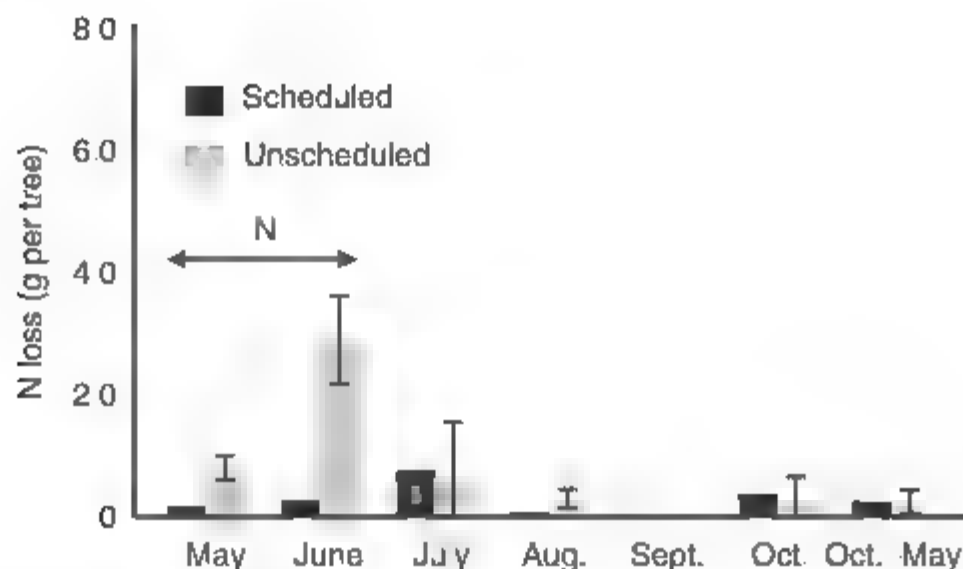


Fig. 12.13. Seasonal nitrogen (N) losses beneath the root zone for 2-year-old 'Gala'/M 9 apple trees in response to irrigation either applied to meet evaporative demand (scheduled) or at a fixed rate (unscheduled). Vertical bars represent mean value ± 1 standard error

translocation out of the leaves (Forshey, 1963). Autumn application of foliar urea makes use of the natural mechanism of withdrawal of nitrogen from leaves during senescence to augment tree nitrogen status for growth the following spring. Increased ovule longevity the following spring has been demonstrated with autumn applications of foliar urea. In pot studies with young trees, foliar nitrogen withdrawal ranged from 23 to 70% (Titus and Kang, 1982). However, Khemura *et al.* (1998) reported that, in mature spur and standard 'Delicious' trees, very little nitrogen derived from autumn foliar applications was found in any tissues the following season. There is some evidence that, for trees with sufficient nitrogen at senescence, foliar-applied urea may only replace leaf nitrogen that would normally be withdrawn, rather than augmenting it. Thus autumn applications of urea would be most useful in trees with low nitrogen status.

In summary, supplying fertilizer nitrogen to meet tree requirements should take into account the management of nitrogen derived for growth both from plant storage and from root uptake. The natural cycling of nitrogen in the tree described above gives the opportunity to manipulate tree nitrogen status in both the current and the future growing season. Fertigation offers a relatively efficient way to supply nitrogen if water is well managed. For trees receiving broadcast nitrogen, a low-input strategy for nitrogen management may be to reserve ground applications in the spring for trees with very low nitrogen status and to supply nitrogen either on the ground after harvest and/or by foliar urea spray in the autumn to trees of adequate nitrogen status. In all cases, the need for nitrogen fertilizer applications should be based on tree performance and, where possible, measurement of residual nitrate concentration in the soil.

12.7.2 Phosphorus

12.7.2.1 Soil availability

Phosphorus solubility is low in most soils, with the result that concentrations of readily available soluble phosphorus in soil solution

are very low, often in the p p b. range. This is a consequence of the propensity for phosphorus absorption and precipitation in the soil, especially as calcium phosphates at soil pH above 7 and as iron and aluminium phosphates below pH 4. Optimum phosphorus availability thus generally occurs in the mid-pH range between acid and basic pH conditions. Soils also vary, however, in their ability to maintain adequate phosphorus in soil solution (a soil's phosphate buffer capacity (PBC)). High-PBC soils require much higher phosphorus additions than low-PBC soils to achieve the same soil-solution phosphorus concentration. High-PBC soils also require higher rates of phosphorus fertilizer in order to achieve effective downward movement of phosphorus into the main rooting zone in orchards.

As a result of low soil-solution phosphorus concentration and the low rooting density of apple trees, phosphorus uptake in apple is strongly dependent upon desorption of phosphorus from the soil matrix and its diffusion to tree roots. Consequently, soil properties such as low temperature and moisture contents, which decrease desorption and diffusion, also decrease phosphorus uptake. It has been difficult to develop a meaningful soil extract that adequately simulates all factors affecting phosphorus uptake for apple, whose roots are also known to be infected by vesicular-arbuscular endomycorrhizae, which in themselves stimulate tree phosphorus uptake. As a result, limited use has been made of various extractable soil phosphorus determinations to design phosphorus-fertilization programmes. Orchards with soils low in extractable phosphorus, regardless of the extractant used, are most likely to respond to phosphorus fertilization. In contrast, apple growth has been stimulated via application of high rates of phosphorus in the planting hole at sites otherwise testing at medium and even high phosphorus levels.

12.7.2.2 Tree phosphorus demands

The absolute phosphorus requirements of apple trees are small relative to other nutrients (Table 12.1). Plant phosphorus is a factor

in energy transfer and is a constituent of phytic acid storage compounds and nucleic acids. Limited research on phosphorus uptake characteristics of apple rootstocks under field conditions by Bhat (1983) indicated that solution phosphorus concentrations at which phosphorus inflow ceases to increase are higher for apple than for most other species. Thus, maintenance of high soil-solution phosphorus for extended periods of time should result in high phosphorus uptake. High phosphorus demand in apple trees occurs during periods of considerable meristematic activity (of which phosphorus is an important regulator) as roots and shoots emerge, particularly at planting. Hansen (1980) has indicated from pot experiments using young 'Golden Delicious'/M.9 that total phosphorus uptake is about 50% lower in fruiting than in non-fruiting trees. Nevertheless, annual phosphorus requirements can be high early in the growing season in fruiting trees when extensive cell division is occurring in developing leaves and fruitlets at a time when root length is at a minimum. Increased incidence of low-temperature breakdown of stored fruit has been associated with low phosphorus concentrations of certain cultivars, including 'Bramley' and 'Cox's Orange Pippin' apples in the UK and 'McIntosh' apples in North America.

Unequivocal indicators of insufficient phosphorus have rarely been observed in the field on apple. Taylor and Goubran (1975), working with phosphorus-deficient apple trees in Australia, indicated that symptoms are frequently an expression of reduced rates of meristematic activity and include accumulation of soluble nitrogen and anthocyanins, resulting in dark green leaves with purple tints in autumn. Also noteworthy was retarded bud burst and reduced flowering of phosphorus-deficient trees. Similarly, Benson and Covey (1979), working with 'Golden Delicious' apple growing in nutrient solution, indicated that phosphorus deficiency was characterized by reduced leaf size and shoot growth but showed no visual, morphological signs of deficiency. These observations indicate that it can be difficult to diagnose phosphorus deficiency from field symptoms. From studies involving young phosphorus-

deficient trees, adequate mid-terminal-leaf phosphorus concentrations are between 0.20 and 0.30% dry weight (DW), usually exceeding thresholds developed for mature fruiting trees (Table 12.2). Desirable fruit phosphorus concentrations are likely to vary by cultivar but have also been suggested for cultivars (Table 12.2) where an association between low fruit phosphorus and reduced fruit quality has been established.

12.7.2.3 Orchard phosphorus management

The traditional belief has been that apple is unlikely to respond to phosphorus fertilization, as documented in numerous phosphorus-fertilizer trials (Childers, 1966). Nevertheless, sufficient responsive sites have now been identified from a range of fruit-growing areas for the possibility of growth and yield responses to surface application of superphosphate or mono- and di-ammonium phosphate not to be ruled out for apples grown on soils testing very low in extractable phosphorus.

Application of high rates of soluble ammonium-phosphate fertilizers directly in the planting hole has been widely used in the Pacific Northwest of North America as a method of improving the establishment and accelerating the vegetative growth and initial yield of newly planted apple trees. The method seems particularly effective where soils are being replanted and have previously been fumigated. Phosphorus is usually applied at high rates (100–150 g per planting hole), well dispersed in the soil to avoid salt toxicity, and can be effective over a range of extractable soil phosphorus. Similar initial growth and yield improvements have been achieved by fertigation of relatively high rates of phosphorus (10–20 g P per tree) early in the establishment year. Both of these soil-application methods result in temporary elevation of soil-solution phosphorus concentration in the main rooting zone and take advantage of the previously described potential for high phosphorus uptake of apple roots.

Foliar application of soluble phosphorus compounds has successfully augmented the phosphorus nutrition of apple. Sprays have usually been applied to improve fruit qual-

ity early in the season (within 4–6 weeks of bloom) during the period of fruit cell division. For example, multiple weekly sprays of 1% potassium dihydrogen phosphate augmented fruit phosphorus concentration and reduced low-temperature breakdown in certain cultivars, including 'Bramley', 'Cox's Orange Pippin' and 'McIntosh' (Table 12.5)

12.7.3 Potassium

12.7.3.1 Soil availability

The total potassium content of most soils can be as high as 4% (average 2%) but soil-solution concentrations can be quite low, since much of the potassium is unavailable to plants due to its incorporation within the structure of many soil minerals. Soluble potassium is in equilibrium with potassium adsorbed on negatively charged exchange sites on the surfaces of clay minerals and organic matter. Soils with high contents of certain clay minerals, including illite and vermiculite, have a particular affinity for strongly adsorbing potassium within their structure. Such soils with 'high potassium-fixation capacity' require higher rates of potassium application to achieve the same increases in soil-solution potassium concentration as could be achieved by application of lower rates to soils with low clay content. In an analogous manner to phosphorus, potassium supply to plant roots depends mainly on the diffusive flux that a soil can maintain in the direction of plants. Thus, light-textured soils with high sand contents and a tendency to droughty conditions are more likely to be potassium deficient, especially for apple trees, which have low root densities. The potassium status of orchard soils can be approximated by determination of the potassium concentration in a variety of soil extracts, including neutral, 1 M ammonium acetate (Grimme and Nemeth, 1978). Soils that result in potassium deficiency of apple usually have low extractable potassium. However, as with many soil tests, 'available potassium' is often poorly correlated with apple tree potassium uptake over a range of soils and climates.

12.7.3.2 Tree potassium demands

Whole-tree K demands of apple are similar in magnitude to those of nitrogen (Table 12.1), with leaf concentrations second to nitrogen and fruit concentrations exceeding all other mineral nutrients. Potassium is mobile within the phloem, so that fleshy fruit are well supplied with potassium. Fruit are such strong sinks for potassium that whole-tree partitioning studies indicate that fruiting trees have higher potassium uptake per unit of root dry mass than non-fruiting trees. At the same time, heavy crop loads decrease leaf potassium concentration.

Severe potassium deficiency results in symptoms typified by marginal leaf browning and scorch on older basal leaves of new year extension growth, the mobile nutrient potassium being preferentially translocated to younger leaves (Plate 12.1). Symptoms appear from mid- to late summer as fruit potassium demands increase. At advanced deficiency, leaves can have irregular edges as dead tissue breaks off. Spur leaves subtending fruit can also be affected, developing an irregular chlorotic surface during midsummer, which progresses into interveinal browning and marginal leaf scorch by fruit harvest. Since potassium is the major positively charged ion absorbed by apple, compensatory uptake of other positively charged ions (especially magnesium and calcium) occurs under conditions of severe deficiency. Potassium-deficient trees are therefore often characterized by unusually high leaf magnesium concentrations. Severe leaf symptoms commonly occur when leaf potassium concentrations are less than 1%. Such reductions in leaf photosynthetic capability frequently reduce fruit size and yield. Amelioration of potassium deficiency can increase fruit red colour and titratable acidity, but such effects are often not apparent when tree potassium status is adequate. Potassium deficiency can also impair tree water relationships, because of the role potassium plays in the proper functioning of stomata.

Frequently, apples with calcium-related physiological disorders, such as bitter pit or

poor storage quality, have high fruit potassium/calcium ratios. However, calcium content appears to be the critical factor and the effect on storage and fruit quality of increased fruit potassium concentration when calcium supply is adequate is unclear. Elimination of potassium deficiency, however, improves fruit yield and quality.

12.7.3.3 Orchard potassium management

It is generally recognized that moderate to heavy broadcast application of potassium salts to the soil surface increases available potassium to the rooting depth in most orchard soils (Boynton and Oberly, 1966). Most potassium salts appear to be suitable potassium sources, including potassium chloride, potassium sulphate, potassium-magnesium sulphate and potassium nitrate, with some advantages to the application of sulphate salts when high rates are required or soils are saline. Details of the positive responses of apple to soil-applied potassium, often at rates of 50–100 kg potassium ha⁻¹, have been reviewed (Forshey, 1969; Cummings, 1985). Less certain are benefits from potassium application when leaf concentrations exceed the low range (above 1.5%). However, it is probably important to moderate potassium applications in order to ensure a favourable calcium/potassium balance, which will optimize quality and storability of the apple fruit. Of the leaf nutrients, magnesium is most adversely affected by high applications of potassium.

Fertigated potassium is readily available in most soils, including those which normally 'fix' large quantities of broadcast potassium (Uriu *et al.*, 1980). For example, annual fertigation of 15 g K per tree successfully prevented the development of growth-inhibiting potassium deficiency in drip-irrigated high-density apple orchards on sandy soils (Nielsen *et al.*, 1998).

Few instances have been observed where apple trees have responded to foliar potassium applications – in part, because of the large quantities of potassium required for optimum growth and the success in ameliorating deficiency via soil application.

12.7.4 Magnesium

12.7.4.1 Soil availability

Magnesium, like potassium, occurs in the soil in different forms, including the relatively unavailable magnesium contained in the structure of soil minerals, exchangeable magnesium adsorbed on organic matter and clay minerals and soluble magnesium dissolved in the soil solution. Unlike potassium, magnesium is not susceptible to specific fixation within the structure of clay minerals. The proportion of magnesium as a fraction of all exchangeable cations is usually second to calcium and exceeds that of potassium. As a consequence, soil-solution concentrations are relatively high and mass flow, rather than diffusion, is capable of supplying the magnesium needs of apple trees. Magnesium availability is, however, affected by the ionic balance between it and other positively charged cations, including K⁺, Ca²⁺, NH₄⁺, Mn²⁺ and H⁺. Thus magnesium deficiencies may be induced in heavily limed or potassium fertilized soils. Soil pH also affects magnesium availability, which is usually optimum in slightly acid soils of pH 5–7. Below pH 5, H⁺ and Al³⁺ antagonisms are common, while, above 7, Ca²⁺ predominates.

The availability of magnesium varies with soils, usually being lower for coarse-textured, leached soils formed on parent materials containing few magnesium-containing minerals and high on soils where leaching is low and high-magnesium parent materials, such as basalts or dolomites, predominate. It is possible to estimate plant-available magnesium by using an extractant, such as neutral, 1 M ammonium acetate, to measure exchangeable and soluble magnesium. In this way, soil-testing laboratories can distinguish orchard soils low in available magnesium and susceptible to the development of magnesium deficiency.

12.7.4.2 Tree magnesium demands

The apple tree's quantitative requirements for magnesium are less than for potassium and calcium (Table 12.1). An important fraction of total plant magnesium (usually 15–20%) is required as a constituent of the

chlorophyll molecule and the ion serves important biochemical functions in activating enzymes involving phosphorylation, activation of ribulose biphosphate carboxylase and protein synthesis (Mengel and Kirkby, 1982).

Deficiencies of magnesium are most apparent in leaf tissue. Symptom expression varies with the severity of the disorder and the susceptibility of the apple cultivar. For example, 'McIntosh' apple is more prone to magnesium deficiency than 'Delicious'. Interveinal leaf chlorosis and yellowing usually develop on older leaves at the base of the new year's growth late in the season as fruit size increases (Plate 12.2). Since magnesium is mobile in the phloem, it is preferentially translocated to young shoot leaves and developing fruit. Depending on the severity of the deficiency, brown interveinal necrotic blotches, known as leaf scorch, can develop, coalesce and, for some cultivars (e.g. 'Newtown') develop into chlorotic and 'scorched' edges difficult to distinguish from potassium deficiency. Severe deficiency can result in leaf curling and premature defoliation. The resulting reduction in canopy photosynthesis can also reduce fruit size and lead to premature fruit drop. Mild magnesium deficiencies do not necessarily result in a growth and yield depression, since the photosynthetic activity of the remaining unaffected green leaves can be enhanced (Ford, 1966). In general, magnesium deficiency is unlikely when leaf magnesium concentrations exceed 0.26%, while leaves with concentrations below 0.20% are likely to exhibit the magnesium deficiencies previously described (Table 12.2).

12.7.4.3 Orchard magnesium management

Application of magnesium-containing materials to orchard soils can improve the long-term magnesium nutrition of apple trees, as long as a meaningful alteration in soil magnesium status, especially relative to the other soil cations, can be achieved in the main rooting zone (Mason, 1964). Failure to achieve this may explain reported ambiguities concerning the effectiveness of soil magnesium applications (Boynton, 1947). For

example, application of magnesium-containing dolomite limestone is likely to be effective in acid soils with low exchange capacity and less effective where soil pH and calcium content are high. Similarly, applications of magnesium sulphate ($250 \text{ kg Mg ha}^{-1}$) did not eliminate symptoms for deficient trees in the short term when soil potassium levels were high (Woodbridge, 1955) or for deficient rootstocks when low annual rates ($40\text{--}60 \text{ kg Mg ha}^{-1}$) were made for 8 years (Ford, 1964). A caution to the indiscriminate application of soil magnesium in orchards is the increased incidence of bitter pit observed in susceptible cultivars after the addition of magnesium to poorly buffered sandy soils (Van der Boon *et al.*, 1966).

There have been few reports of effective fertigation of magnesium on apples, despite the ready solubility of various magnesium salts applied as foliar sprays. Multiple sprays (usually two to five) of magnesium salts have ameliorated magnesium-deficiency symptoms. Such sprays are best applied post-bloom and are usually recommended for the period of rapid shoot growth (late May–early July in northern latitudes). They have eliminated decreased fruit set, normally associated with severe magnesium deficiency (Ford *et al.*, 1965). A 2% (w/v) magnesium sulphate (Epsom salt) solution has been commonly used, although other soluble magnesium salts, including magnesium chloride and magnesium nitrate, have worked (Table 12.5). Some soluble magnesium chelates have been ineffective because of low magnesium concentration (Nielsen and Hoyt, 1984).

12.7.5 Calcium

12.7.5.1 Soil availability

Most soils contain large quantities of calcium (3.5% , 35 t ha^{-1}) as a constituent of calcium carbonate, silicate, sulphate and phosphate minerals. Calcareous soils can be particularly enriched in calcium, with contents as high as 10–20%. Calcium usually comprises the bulk of exchangeable cations (65–85%) adsorbed to organic matter and inorganic soil colloids

and has the highest concentration (50–100 p.p.m.) of any cation in soil solution. Thus, plant requirements for calcium are usually satisfied by mass flow of water to the root, and low soil calcium is not often a limitation to growth. An exception can occur for old, leached and acidic soils, which may have extremely low calcium contents. The presence of high concentrations of other cations also inhibits uptake of calcium. Soil calcium status is intimately associated with soil pH, since higher calcium saturation of the exchange complex occurs as pH increases. Soils can be tested for their extractable calcium content, but pH measurements usually determine the necessity of applying calcium-rich liming materials to the soil.

12.7.5.2 *Tree calcium demands*

Apple wood contains more calcium than any other mineral element, with the result that orchard requirements to maintain top and root structures are higher than for all other nutrients (Table 12.1). Calcium transport to the root surface within the soil is usually high but, within the plant, calcium movement is slowed by ion exchange in the xylem. Calcium is also relatively immobile in the phloem, due to restricted phloem loading. As a consequence, plant organs more dependent upon phloem supply, such as the fruit of the apple, frequently have difficulties obtaining sufficient amounts. Calcium serves important functions within the plant, including regulation of cellular behaviour and maintenance of cell integrity and membrane permeability (Mengel and Kirkby, 1982).

In apple, the effects of inadequate levels are manifested primarily in fruit rather than leaves. Leaf deficiency symptoms are rarely seen under orchard conditions but have been described for apples grown in nutrient solutions containing low calcium concentrations. The descriptions of Shear (1971) for the cultivar 'York Imperial' are pertinent and include first an upward cupping of the youngest shoot leaves, followed by the development of veinal and interveinal chlorosis, with the eventual development of chlorotic spots and necrotic tissue on leaf edges. Fruit symptoms may be more prominent and include abnor-

mal skin bronzing, late-season darkening of lenticels and sometimes severe fruit splitting by harvest. It is now well established that inadequate calcium supply is related to many physiological disorders in the storage organs of fruits and vegetables (Shear, 1975). For apples, calcium-related disorders include bitter pit (Plate 12.3), cork spot, cracking, internal breakdown (Plate 12.4), Jonathon spot, lenticel blotch, water-core and low-temperature and senescent breakdown. In general, improved calcium nutrition is also considered to provide broad-spectrum protection against many postharvest pathogens.

It is therefore not surprising that considerable effort has gone into understanding the inflow of calcium into apple fruit. Different seasonal patterns have been measured, ranging from the bulk of inflow occurring in the 4–6-week period of cell division following bloom (Wilkinson, 1968) to a steady increase throughout the growing season (Faust, 1989). Regardless of the temporal pattern of absolute calcium accumulation, calcium concentration declines as fruit size reaches a maximum at harvest. Concentration gradients also develop within the fruit, with minimum values measurable immediately beneath the skin at the calyx end of the fruit. Actual calcium concentrations achieved in a given year are therefore strongly affected by final fruit size and hence crop load. A large yield tends to produce smaller fruit of higher calcium concentration. A strong genetic effect is also apparent, as different cultivars can achieve different fruit calcium concentrations despite growing under similar environmental conditions. This is illustrated for different cultivars growing in the irrigated fruit-growing region of the Pacific northwest of North America (Fig. 12.3).

The rarity of leaf calcium deficiency in the orchard and the frequency and importance of fruit calcium disorders indicate that fruit calcium concentration thresholds are a more useful indicator of an orchard's calcium status. Unfortunately, such values are likely to be cultivar-specific and dependent upon the analysis method and the part of the apple analysed. For example, recommended whole-fruit calcium concentrations (Table 12.2) may not be pertinent for 'Cox's Orange Pippin',

which has a deficiency threshold of 5 mg Ca 100 g⁻¹ fresh weight. A critical peel calcium concentration of 700 mg kg⁻¹ DW was recommended for 'Baldwin' apple, although year-to-year variation in critical calcium values was also apparent (Drake *et al.*, 1974).

12.7.5.3 Orchard calcium management

Considerable effort has been made to understand factors influencing orchard calcium nutrition, because of the importance of this nutrient for fruit quality. Many of the details have been reported in comprehensive reviews on the subject (Vang-Petersen, 1980; Himelrick and McDuffie, 1983).

Applying large quantities of calcium compounds to the soil via liming can increase leaf calcium concentration but not fruit calcium concentration, as indicated by persistence of calcium-related physiological disorders despite the liming of acidic soils. Thus, lime applications are made primarily for pH adjustment, rather than as a source of calcium. Soil application of soluble calcium salts, such as calcium nitrate, is unlikely to alter the calcium status of most fruit, except in very acid soils (Van Lune, 1984). Similarly, successful use of fertigation of soluble calcium to increase fruit calcium concentration has not been reported, possibly because the calcium concentration of fertigating solutions is often less than the calcium concentrations measured in soil solution.

Successful augmentation of fruit calcium concentration and diminution of calcium-related disorders have been achieved by application of multiple sprays of soluble calcium salts directly to the fruit surface prior to harvest. Calcium chloride is usually recommended, although Ca(NO₃)₂ can also be effective (Table 12.5). The chloride form is cheap, contains a higher calcium concentration and avoids additional application of nitrogen to fruit. Some materials containing, for example, chelated calcium at low concentrations have been ineffective as foliar calcium sources. Recommended concentrations of the salt are usually about 0.5% (w/v) but single-spray applications as high as 4% have been effectively applied just prior to harvest when the resulting leaf damage has been assumed to be

unimportant. The amount of calcium absorbed by the fruit is directly related to the number of sprays applied, so the number of recommended sprays depends upon the calcium status of the fruit. Four or five sprays at 7-10-day intervals late in the growing season have eliminated serious occurrences of bitter pit in susceptible cultivars growing in semi-arid climates where little precipitation occurs to wash the applied calcium from the fruit. Late-season sprays are particularly effective, since the intended fruit target is larger and since many calcium disorders develop late in the season or postharvest during storage. Early-season sprays may be appropriate for calcium-related disorders, such as corking, which develop early in the season.

Calcium can also be applied postharvest to picked fruit by dipping, vacuum or pressure infiltration with CaCl₂ salts with concentrations as high as 2% (w/v). The advantages of such treatments to reduce postharvest decay have been described in detail by Conway *et al.* (1992).

12.7.6 Sulphur

12.7.6.1 Soil availability

Most sulphur contained in soils (90-95%) occurs in organic compounds, while the remaining inorganic forms usually occur as sulphates in normally aerated orchard soils. Inorganic forms are readily leached in humid regions and thus can occur in high concentrations in ground and runoff waters. There is little effect of soil pH on sulphur availability. No single extraction technique has found universal acceptance for analysing available sulphur in soils for most crops (Kowalenko, 1993), with the consequence that little information is available to relate the performance of apple trees to the supply of soil sulphur. Inadequate availability of sulphur is most likely to occur in orchards with leached soils, low in organic-matter content and receiving limited sulphur.

12.7.6.2 Tree sulphur demands

Apple requirements for sulphur are similar in magnitude to those for phosphorus, with absorbed SO₄-sulphur incorporated struc-

turally into sulphur-containing amino acids, proteins and coenzymes. Thus deficiencies of sulphur inhibit protein synthesis and reduce tree growth. Sulphur deficiencies have rarely been observed on apples in the field. A notable exception was described by Benson *et al.* (1963) in Washington State. Deficient apple trees exhibited a chlorosis on younger leaves at the top of the plant, with leaf colour progressing from light green, light yellow to yellow, eventually affecting the whole plant, stunting growth and reducing yield. The trees did not respond to nitrogen or iron applications, deficiencies of which can result in similar symptoms. Severe sulphur-deficiency symptoms on shoot-tip leaves developed when tissue SO_4 -sulphur concentrations were less than 100 p.p.m. (0.01%). As a result of the rarity of sulphur deficiency, there is some question as to how this concentration relates to the more easily measured total sulphur value, although a critical total sulphur concentration of 0.1% has been suggested (Table 12.2).

12.7.6.3 Orchard sulphur management

Many orchards have substantial natural inputs of sulphur with precipitation and irrigation. Unintended applications of sulphur can also occur via sulphur-containing fertilizers and pesticides. For example, sulphate salts of ammonium (24% S), calcium (19% S), potassium (17–22% S), magnesium (14% S) and zinc (11% S), as well as superphosphate fertilizer (12% S), may be applied as a source of other nutrients but simultaneously augment sulphur. Some concern has been expressed that sulphur inputs to orchards are decreasing as control of air pollution reduces the sulphur content of precipitation and the use of sulphur-containing fertilizers and pesticides in orchards declines.

Amelioration of inadequate sulphur nutrition was demonstrated in deficient Washington State orchards via both broadcast application of sulphur-containing fertilizers to the soil and spray applications of soluble sulphate salts to foliage. It is also likely that soluble sulphate salts could be effectively fertigated, although little research has been reported. Most organic amend-

ments also have significant sulphur content, approximating 10% of their nitrogen content.

12.7.7 Boron

Boron has been the subject of numerous review articles, including a recently published book (Gupta, 1993), which provides additional useful information concerning this nutrient.

12.7.7.1 Soil availability

Total boron contents of orchard soils normally range from 20 to 200 p.p.m., often with only a small portion (< 5%) of the total available to plants. Boron, dissolved in soil solution as the uncharged boric acid molecule, is plant-available but is also easily leached from sandy soils. Organic matter can contain appreciable quantities of boron, which are available to plants upon mineralization. Boron adsorption to clay and organic matter increases with pH, reaching a maximum sorption and minimum solution concentration at pH 8–9. Thus leached sandy soils that are low in organic matter are susceptible to boron deficiency, particularly after liming. In arid regions, high concentrations of soluble boron salts can accumulate in soil or irrigation waters, creating a potential for toxicity. The amount of boron extracted after boiling soil in water is commonly used as a measure of plant availability. Values below 1 p.p.m. or above 5 p.p.m. indicate potential for deficiencies or toxicities of boron, respectively.

12.7.7.2 Tree boron demands

In apple, boron is required at low (p.p.m.) concentrations in leaves and fruit. In general, boron maintains plant meristematic activity and cell-wall stability and functions as a coenzyme in the formation and transport of sucrose. Apple has less sensitivity to boron deficiency than other tree fruits, such as peach. However, deficiency of boron in apple has serious consequences, which are manifested first in reproductive structures, including flowers and fruit. Inadequate boron nutrition has been associated with 'blossom

blast', a drying and shrivelling of flowers at bloom, distinguishable from frost damage by the longer retention time of the damaged tissue on the tree (Plate 12.5). Since pollen-tube growth is also stimulated by boron, reduced fruit set under conditions of low boron status can further contribute to yield reductions. Insufficient boron has also been associated with fruit disorders. Commencing soon after fruit set, water-soaked areas develop and progress into dry, hard, corky masses within the fruit, which can result in external depressions and corking and cracking of the extended skin surface (Plate 12.6). These disorders can develop early on fruit less than half final size and may result in early drop of affected fruits, further reducing yield. This disorder has also been referred to as drought spot, since boron deficiency can be induced by low-moisture conditions preceding a period more favourable to tree growth. With increased severity of the deficiency, abnormal growth of shoot tips occurs and the youngest leaves are misshapen and wrinkled and develop red veins and interveinal chlorosis. Death of the terminal bud and small areas of the inner bark and cambium near the growing tip results in the dieback of shoots. It is also likely that root tips suffer dieback, but this often goes unnoticed. Severe deficiency can result in rough and cracked bark (apple measles) due to the death of some bark tissue in young branches.

Boron is the nutrient with the narrowest of margins between deficiency and toxicity. Apple is moderately sensitive to boron toxicity, which is manifested by delays in flowering and increased incidence of bud death (blind buds). Midrib yellowing of leaves (Plate 12.7), defoliation, shoot dieback and early maturity, increased respiration and reduced storage life of fruits are characteristics of toxicity in apple.

There is likely to be some genetic variation in the sensitivity of different apple cultivars to deficit and toxic concentrations of boron. Nevertheless, boron deficiency has frequently been reported at leaf boron concentrations < 20 p.p.m. and fruit-flesh boron concentrations < 0.8 p.p.m. (fresh weight) (Table 12.2). Toxicity thresholds are less certain, but concern has been expressed for bud

health at leaf boron concentrations as low as 50 p.p.m. (Hansen, 1981) but more generally in excess of 70 p.p.m.

12.7.7.3 Orchard boron management

An overriding consideration in the management of boron nutrition in orchards is the narrow range between boron deficiency and toxicity. Boron can be effectively applied to orchard soils to correct deficiency as various soluble boron fertilizers, including borax (sodium tetraborate, 11% B). Rates are rather low, usually only $1.2 \text{ kg B ha}^{-1} \text{ year}^{-1}$. Application of rates as low as these can be physically difficult, so sometimes higher rates are applied once every 3 years or applications are made as boronated forms of other macronutrient fertilizers. Uniform application is important to avoid toxic concentrations. The addition of organic amendments and composts containing boron can also provide sufficient boron for the soil to prevent deficiency.

Given the solubility of many boron compounds, the nutrient can also be fertigated in irrigation water, although care must be taken to avoid over application. Rates as low as 0.3 g B per tree, applied over several weeks, have effectively ameliorated boron deficiency without inducing toxicity. It is prudent, however, in irrigated areas to know the boron concentration of irrigation waters and therefore the amount of boron already applied with water.

Foliar sprays of soluble boron compounds, such as Solubor (20% B), are highly effective and are often safer than soil applications, since much lower rates and concentrations of compounds (0.2–0.5% w/v) can be applied. Solubor is also compatible with other commonly applied oils, emulsions and pesticides. A common strategy for maintenance of boron in apple orchards is to make a single spray early in the spring, prior to bloom (Table 12.5). This can be useful, particularly if pollination conditions are suboptimal. Recently, sprays applied postharvest in the autumn have also been effective the following spring as a consequence of the mobility and storage of sprayed boron in apple trees (Brown and Shelp, 1997). Several sprays may be required to correct severe boron deficiency.

12.7.8 Zinc

A comprehensive review of soil, plant and management factors associated with zinc nutrition of horticultural crops, including apples, has recently been completed by Swietlik (1999).

12.7.8.1 Soil availability

Total soil zinc contents of orchard soils are very low, ranging from 10 to 300 p.p.m., and average about 80 p.p.m. Total zinc contents relate to parent material, with soils originating from basic igneous rocks usually higher in zinc than soils derived from silica-rich minerals. Zinc occurs in the soil as relatively insoluble forms within the structure of primary and secondary minerals or precipitated on solid surfaces of carbonates and iron and manganese oxides.

Forms more available to plants include exchangeable zinc, associated with reactive clay and organic matter, or zinc dissolved in the soil solution. Zinc, like phosphorus, occurs at very low (p.p.b.) concentrations in solution, so that zinc supply to the root depends upon diffusion, rather than mass flow, and is adversely affected by factors inhibiting diffusion. Soil pH strongly affects zinc availability, decreasing zinc solubility 100-fold per unit increase in pH. Thus zinc deficiency is commonly associated with neutral to high-pH soils, especially those containing free calcium carbonate. However, acid and organic soils low in zinc and soils high in phosphorus can also be zinc-deficient. Limited research has been undertaken to determine the best soil extraction method for predicting zinc status of apple trees, although Neilsen *et al.* (1988), working with British

Columbia orchards, found soil zinc extracted by 0.25 M MgCl_2 related more closely to zinc-deficiency symptoms of apple than the more widely used diethylenetriaminepenta-acetic acid (DTPA) extract (Table 12.9)

12.7.8.2 Tree zinc demands

Apple has a low requirement for zinc but is also highly susceptible to zinc deficiency. Zinc functions in several plant enzyme systems and several plant biochemical functions, including pH regulation in plant cells, protection from O_2^- damage and synthesis of RNA and tryptophan – a precursor of indoleacetic acid, which is involved in shoot elongation. Symptoms of zinc deficiency frequently occur in early spring and include chlorosis (yellowing) of the youngest shoot leaves, which are often somewhat undersized (Plate 12.8) and narrower than normal (a condition referred to as 'little leaf'). Mobility of zinc within the plant is poor, so little zinc is translocated from old to young leaves. Yellowing occurs between leaf veins and is less symmetric than similar symptoms observed on basal leaves with manganese deficiency. Zinc deficiency may also result in blind bud and rosetting (small basal leaves forming on the shortened terminals and lateral shoots of the current season's growth). Extreme deficiency, which is rare, can result in shoot defoliation and dieback and the production of undersized, misshapen and poorly coloured apples, which ripen early and lack flavour. Zinc-deficiency symptoms can be very sporadic in occurrence, with all or only some shoots on a tree affected and with an occasional or many trees affected within an orchard block (Plate 12.8). There can be considerable overlap in leaf zinc con-

Table 12.9. DTPA-extractable zinc, copper, manganese and iron values determined for deficient, marginal and sufficient soils for non-orchard crops (adapted from Tisdale *et al.*, 1993, p. 318).

Soil status	Zinc (p.p.m.)	Copper (p.p.m.)	Manganese (p.p.m.)	Iron (p.p.m.)
Probably deficient	0–0.5	< 0.2	< 1.0	0–2.5
Marginal	0.6–1.0	–	–	2.6–4.5
Sufficient-high	> 1.0	> 0.2	> 1.0	> 4.5

centrations of healthy and deficient trees, although concentrations much below 14 p.p.m. are a cause for concern (Table 12.2). Zinc toxicity has rarely been reported for apple but has been observed when unsprayed leaf zinc concentrations range from 130 to 160 p.p.m. (Orphanos, 1982).

12.7.8.3 Orchard zinc management

Inadequate zinc is widely considered the most common micronutrient deficiency of apples. Despite the successful amelioration of zinc deficiency in many agronomic crops via the application of 4–10 kg Zn ha⁻¹ as zinc sulphate, limited emphasis has been placed on soil zinc application in apple orchards. Increased zinc uptake of apple has, however, occasionally been reported in orchards where soluble zinc applications have been banded at much higher rates or co-applied with organic amendments under acidifying conditions. Fertigation of soluble zinc compounds is possible but recommended rates and techniques on a range of soils have not been widely developed.

In contrast, spray applications of zinc are the most common practice for successful, immediate correction of zinc-deficiency symptoms and are often applied as annual maintenance sprays (Table 12.5). Unfortunately, there is little residual effect from such sprays, due to the limited movement of zinc from sprayed to unsprayed leaves. Various late-dormant sprays, including zinc sulphate, have been successfully applied but, when fruit are on the tree, chelated forms are usually preferred, to avoid fruit damage. Otherwise, there has often been little practical difference in the effectiveness of various forms of similar solubility and zinc concentration. Direct trunk injection of zinc may be possible but has not been widely practised.

12.7.9 Iron

12.7.9.1 Soil availability

Total iron content of soils is high, since iron, on average, comprises about 5% by weight

of the soil as a constituent of primary silicate, oxide, hydroxide and carbonate minerals and secondary clay minerals, such as illite. Iron has, however, such low solubility that insufficient amounts can be supplied to plant roots by mass flow. Iron movement to roots in soils is, however, increased by its tendency to form more soluble complexes, including chelates, with organic compounds. Soil pH is an important control on iron solubility, with Fe³⁺, the predominant soluble iron form in aerated orchard soils, decreasing 1000-fold in solubility for each unit increase in pH and reaching minimum solubility at pH 6.5–8.0. Iron availability is thus extremely low in the approximately 25% of the world's arable land that is calcareous with pH near 8.2. High bicarbonate concentrations in soil solution or irrigation water can further reduce the availability of iron to plants. Since compacted or saturated soils can increase soil-solution bicarbonate concentration, these soil conditions also increase the probability of iron deficiency on soils of high pH. Uptake of iron from soil solution is also inhibited by competition from high concentrations of ions such as Zn²⁺, Mn²⁺, Cu²⁺, Ca²⁺, Mg²⁺ and K⁺. It is for this reason that high concentrations of other metals in unbuffered sandy soils can induce iron deficiency. Limited use of soil extractants, such as DTPA, has been made to determine the iron status of orchard soils (Table 12.9).

12.7.9.2 Tree iron demands

Iron is a constituent of the haem complex (a naturally occurring plant chelate involved in electron transfer in a number of important plant enzymes) (Mengel and Kirkby, 1982). In green leaves there is a good correlation between iron supply and chlorophyll content. Inadequate iron nutrition results in abnormal chlorophyll development, so that deficiency begins as an interveinal chlorosis on younger leaves resulting in prominently green veins (Plate 12.9). These leaves may become completely white and devoid of chlorophyll and may even scorch late in the summer. The resultant reduction in photosynthetic capability also reduces the weight and area of affected leaves, with the yield and quality of

apples adversely affected as the extent and severity of deficiency increases over the whole tree. Further descriptions and causes of iron deficiency have frequently been reviewed, recently by Korcak (1987) for horticultural crops, including apple. A wide range of total iron concentration has been measured in normal leaves (Table 12.2), but deficient leaves can have a higher iron concentration than normal leaves. In contrast, 'active' iron concentration (extracted in 0.5–1.0 M HCl) can distinguish between normal and iron-deficient leaves but is not a reliable diagnostic tool. As a consequence of disruption in normal photosynthesis, iron-deficient leaves often accumulate other minerals, such as phosphorus, potassium and NO_3^- -nitrogen, or organic components, such as citric acid. Apples are less susceptible to iron deficiency than other temperate fruit trees, including peaches and pears, and as a result there has been little research to identify iron-efficient rootstocks, as has been done for peaches. Iron deficiency can be confounded by the occurrence of simultaneous multiple micronutrient deficiencies, including manganese and zinc, so that iron deficiency has also been defined as regreening after the foliar application of an iron spray.

12.7.9.3 Orchard iron management

It can be difficult to ameliorate iron deficiency in apple via application of soluble salts to the soil, due to their tendency to become unavailable to the plant via precipitation. Limited success has been achieved, however, by co-application of FeSO_4 with organic matter and other strongly acidifying fertilizers. Chelated iron compounds can be more soluble in soils, although their effectiveness varies and their cost is high. Iron-EDDHA (ethylenediaminedi-O-hydroxyphenylacetic acid) is particularly effective over a range of soil pH. Little research has been conducted on fertigating iron, although it is likely that the general principles of effective soil application will prevail (i.e. use of chelated iron or other soluble iron sources under acidifying conditions).

Iron deficiency can be corrected by direct application to the foliage of dilute solutions

of FeSO_4 or various iron chelates (Table 12.5). Multiple sprays to actively growing shoots are frequently required and can be moderately effective, but must be reapplied annually. Direct injection of 1% solutions of iron citrate or sulphate into the trunks of fruit trees, including apple, has corrected iron deficiency for several years without serious damage to trunks.

12.7.10 Manganese

12.7.10.1 Soil availability

Total manganese contents of orchard soils are usually higher than those of zinc, ranging from 200 to 3000 p.p.m. and averaging about 600 p.p.m. Manganese can be a constituent of several primary and secondary minerals and occurs as insoluble and oxidized Mn^{3+} and Mn^{4+} forms associated with iron in oxide and hydroxide precipitates in the soil. The reduced form of manganese (Mn^{2+}) is readily available to plants and can occur in soil solution at p.p.m. values, usually exceeding concentrations of the other important micronutrients, zinc and copper. Plant-available manganese is affected by pH in a similar fashion to zinc, decreasing in solubility 100-fold per unit rise in pH. Thus manganese is very soluble when soil pH is below 5.5 and has low solubility in calcareous or limed soils with pH above 7.0. Manganese solubility increases in moist, saturated soils of acid pH, whereas reductions in availability can occur as a result of microbial oxidation. Organic matter can increase or decrease manganese availability, depending upon the stability of the compounds formed by their interaction. Limited use has been made of manganese soil tests for orchards, in part because of the complexity of characterizing a nutritional range extending from deficiency to toxicity (Nielsen *et al.*, 1990). The DTPA micronutrient test is useful for determining manganese status near deficiency in neutral and calcareous soils (Table 12.9).

12.7.10.2 Tree manganese demands

Absolute manganese requirements are small, slightly exceeding tree demand for zinc. Like

Mg^{2+} , Mn^{2+} is required in enzyme reactions involving photosynthesis and carbon assimilation and is preferentially translocated to meristematic tissue in growing shoot tips. Chloroplasts are most sensitive to manganese deficiency. Consequently, manganese deficiency in apple first appears as irregularly shaped, light green spots on the margins and between the veins of basal shoot leaves (Plate 12.10). Interveinal loss of green colour frequently results in prominent green veins. Only rarely does severe deficiency decrease leaf size and shoot growth. Furthermore, the deficiency may be temporary, appearing in the spring, when roots are cold, and disappearing as soils warm. Leaf manganese concentration below 25 p.p.m. may indicate manganese deficiency. In contrast, tree manganese uptake can be very high when soil pH is acid, resulting in manganese toxicity. Internal bark necrosis, also known as 'bark measles', is a trunk disorder associated with excess manganese, which results in the blistering, cracking and peeling of the bark on the trunk, branches and shoots of affected trees (Fig. 11.6). Certain apple cultivars, including 'Delicious' (especially 'Starkrimson'), 'Tydeman' and 'Fuji', are known to be more susceptible to this disorder, which commonly occurs when soil pH is below 5.5 and leaf manganese concentration exceeds 120 mg kg^{-1} .

12.7.10.3 Orchard manganese management

Soil applications to correct manganese deficiency are generally not used for apple and can be ineffective if the soil condition (e.g. high pH) that reduces the soil manganese availability is not altered. Fertigation of soluble manganese compounds is possible, but frequently leaf manganese concentration can be readily increased by fertigation of acidic fertilizers (Table 12.4).

Foliar sprays of $MnSO_4$ and chelated manganese solutions, applied directly to affected leaf tissue, effectively regreen leaves, although multiple sprays may be required if the deficiency is severe (Table 12.5). Direct trunk injection of $MnSO_4$ will also work; however, the preferred treatment is foliar application.

12.7.11 Copper

12.7.11.1 Soil availability

Of the micronutrients required by apple, copper, which is contained in primary and secondary minerals, often has the lowest total concentration in soil, averaging about 10 p.p.m., with values usually ranging from 1 to 50 p.p.m. Much higher concentrations can occur in soils after additions of high-copper materials, including municipal biosolids, pig and poultry manures, mine wastes and copper-containing pesticides. The availability of copper to plants, as with other trace minerals, markedly decreases as pH rises above 7.0. At high pH, copper is strongly adsorbed to clays, iron and aluminium oxides and organic matter. Most of the low concentrations of copper dissolved in solution are organically complexed. There has been little use of soil testing to determine the copper status of orchard soils. The DTPA extractant has successfully identified low and deficient copper sites for other crops (Table 12.9).

12.7.11.2 Tree copper demands

Apple tree copper requirements are among the lowest of all nutrients. Copper is, however, required for chlorophyll synthesis and in several copper-containing enzymes involved in the reduction of molecular oxygen. Copper deficiency of apple is rare but has been reported from orchards in Australia, England, South Africa and the USA. It is characterized by the development of brown and necrotic areas on terminal leaves, accompanied by upward curling and distortion of the leaves. The disorder is often referred to as 'wither tip' or 'summer dieback', since initial leaf symptoms often proceed to defoliation and dieback of shoot tips in the late summer. Severe deficiency results in the cracking and shedding of bark and profuse sucker development from the tree base. Copper deficiency occurs in leaves with concentrations less than 5 p.p.m. Copper toxicity has not been documented for apple but has been observed for other crops, where it has reduced growth.

12.7.11.3 Orchard copper management

When copper-deficiency symptoms occur in apple orchards, they have been eliminated by foliar applications of dilute copper sulphate or copper chloride salts (Table 12.5).

Copper chelates can also be used as foliar fertilizers. Many orchards already receive foliar copper applications via copper-containing fungicides. Soil copper applications, broadcast or via fertigation, might be effective but are generally not used.

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13 Orchard-floor Management Systems

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13.1 General Principles and Objectives in Orchard-floor Management

The methods used to manage weed competition, maintain soil fertility, provide essential soil nutrients and water for trees and promote beneficial biological processes in orchards influence the productivity and sustainability of fruit plantings. The tactics and strategies for managing surface vegetation and soil resources in fruit plantings are referred to as orchard-floor management (OFM) systems (Hogue and Neilsen, 1987). This chapter describes the general principles and objectives for OFM, compares different weed- and soil-management systems used by fruit growers and suggests opportunities for improving the sustainability of fruit growing by optimizing and integrating OFM systems.

Commercial fruit growing requires substantial inputs of resources and expertise, and crop values can approach US\$100,000 ha⁻¹. It costs about US\$20,000 ha⁻¹ to establish a high-density apple orchard and bring it into production, and the profitability of fruit growing is affected substantially by OFM systems (White and DeMarree, 1992; Geldart, 1994; Derr, 2001). Weed competition for essential resources can stunt the growth of young trees, increase winter injury and disease susceptibility and reduce the quantity and quality of yields in mature trees (Hogue and Neilsen, 1987; Welker and Glenn, 1988, 1989; Glenn and Welker, 1989; Merwin and Stiles, 1994). Apple trees do not compete effectively with many weeds for soil nutrients and water, because the trees have relatively sparse root systems that do

not exploit as large a portion of the available root zone as most herbaceous weeds (Atkinson, 1980). Surface vegetation beneath trees must usually be managed to curtail competition for limiting soil resources.

Weed competition with fruit trees can be eliminated by residual herbicide applications that eradicate year-round all surface vegetation. Such 'weed-free' OFM systems increase the short-term availability of water and nutrients, but may be detrimental to both soil and water quality (Merwin *et al.*, 1996; Elmore *et al.*, 1997; Glover *et al.*, 1999). Long-term conservation of soil fertility is especially important in a perennial crop system where good fruit-growing sites are limited and may be replanted continuously for decades or centuries. Stringent climatic and edaphic requirements of fruit trees often restrict orchards to upland sites on well-drained soils near major lakes and rivers, where soil erosion and leaching or runoff of agrochemicals into water resources are potentially serious problems (Logan *et al.*, 1987; Weinbaum *et al.*, 1992; NRC, 1993). From the environmental and economic perspectives, orchard ground covers can provide important benefits – preventing soil erosion, improving water infiltration and

nutrient retention, improving fruit quality (see Plate 13.1) and maintaining or improving soil organic matter and structure (Haynes, 1981; Skroch and Shribbs, 1986; Welker and Glenn, 1988; Moore *et al.*, 1989; Johnson and Samuelson, 1990; Stevenson and Neilsen, 1990; Merwin *et al.*, 1996). For example, after 5 years under different OFM systems in a New York orchard, soil organic matter decreased substantially in mechanical tillage and bare-soil residual pre-emergence herbicide treatments and increased under mowed sod grass and hay-straw mulch treatments (Fig. 13.1). The fundamental challenge for sustainable OFM systems is to achieve a favourable balance between the beneficial aspects of ground-cover vegetation or residues and the negative impacts of excessive weed competition.

To avoid unnecessary or wasteful weed-control measures, it is important to distinguish between weeds (defined as undesirable surface vegetation that reduces crop yield or quality by competing for essential resources without providing compensatory benefits) and ground covers (defined as naturally occurring weeds, synthetic or biomass mulches, cover crops or turf that is managed as a useful part of the crop system).

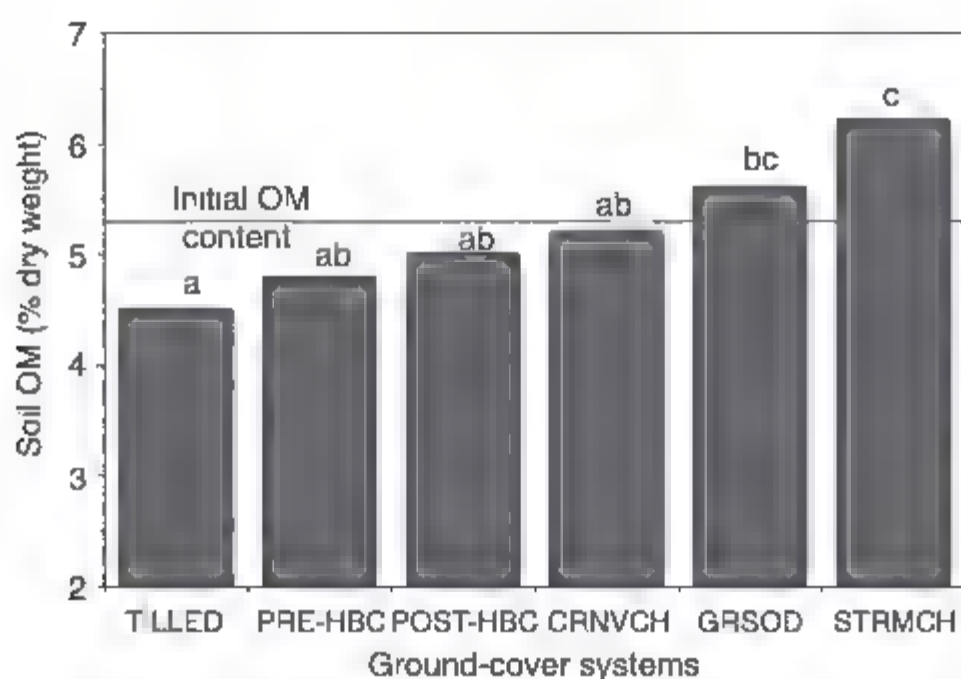


Fig. 13.1. Organic matter (OM) content (% dry-weight basis) in upper 20 cm topsoil after 5 years under different ground-cover management systems. Treatment abbreviations: TILLED, monthly rotavating during growing season; PRE-HBC, pre-emergence applications of paraquat, norflurazon and dicuron herbicides in April each year; POST-HBC, two post-emergence applications of glyphosate herbicide in May and July each year; CRNVCH, 'living mulch' of crown vetch; GRASOD, mowed sod grass of red fescue and perennial ryegrass; STRMCH, 10-cm-deep hay-straw mulch applied each May. Treatment means beneath different letters were significantly different (LSD for $P < 0.05$). (Data are from Merwin *et al.*, 1994.)

It follows from these definitions that ground-cover vegetation may function as weeds in some circumstances and as useful cover crops at other times. The essential objectives in OFM are to maintain sufficient ground cover to protect soil and water resources and to suppress weed competition within critical time spans and surface areas of the orchard. In other words, the optimal management strategy – as with pest insects or pathogens – is to control weeds only if and when they surpass a predetermined threshold where potential crop damage exceeds the cost of control measures and the value of compensatory benefits that ground cover provides for the agroecosystem. These weed-management trade-offs and thresholds are not well understood at present for most crop systems, including orchards.

The level of pest infestation where anticipated crop damage justifies the costs of control measures is known as the damage action threshold or economic injury level for that pest (Pedigo, 1989). This concept is fundamental to integrated pest management (IPM) and utilized widely in disease and insect control – but relatively neglected in weed control (Coble and Morteusen, 1992). Recent studies indicate that temporal (critical times for weed control during the growing season) and spatial (critical weed-free areas beneath trees) damage thresholds can be determined for fruit trees. One study compared tree growth, nutrient uptake and cumulative yield of apple during 8 years in 2.5 m wide strips where weeds were either eradicated year-round with residual pre-emergence herbicide applications or suppressed only from May to August with post-emergence herbicides that allowed substantial regrowth of ground-cover vegetation from September to April (Merwin and Stiles, 1994). Despite potential weed competition during the dormant season, there was no comparative advantage in the completely weed-free OFM system relative to the partially weed-free system. In other studies, with tart cherry (*Prunus cerasus* L.) and apple, early-summer (May–July) weed suppression resulted in substantially better tree growth and yields compared with late-summer weed control

(Gut *et al.*, 1996; Merwin and Ray, 1997; Al-Hinai and Roper, 1999). Glenn and Welker (1996) showed that yield efficiency of mature peach (*Prunus persica* Batsch) trees could be increased and pruning costs decreased by manipulating sod competition and proximity to trees. Other research has demonstrated that fruit quality (blush coloration, soluble solids, firmness and storage potential) can be improved by moderate nitrogen and/or water deficits induced by ground-cover competition at certain times of the growing season (Hogue and Neilsen, 1987; Hipps *et al.*, 1990; Perret *et al.*, 1994; Hornig and Bunemann, 1995; Marsh *et al.*, 1996; Neilsen *et al.*, 1999).

Effective OFM requires understanding the relationship between nutrient uptake and root-growth periodicity in fruit trees and competing weeds, but surprisingly little is known about this topic (Flores *et al.*, 1998). Pioneering research by Head (1966) in non-replicated root-observation chambers indicated bimodal peaks of apple root growth early and late in the growing season of south-east England. Recent research utilizing mini-rhizotrons and soil respiration chambers for replicated observations of apple rootstock growth and respiration rates revealed substantially different trends in root growth, presumably due to climate or soil differences between England and the north-eastern USA (Psarras *et al.*, 2000). For field-grown 'Mutsu' apple trees on M.9 rootstocks in a silt-loam soil, there was negligible root growth early and late during two growing seasons in New York, and the main phases of root, canopy and fruit growth all coincided from late May to mid-July (Fig. 13.2). These observations may help to explain why weed control during early summer months has been most effective in most studies, because this appears to be the period of greatest competition between trees and weeds for soil resources. Further observations of root-growth and nutrient-uptake timing with different rootstocks, soil types and ground cover species are needed to refine OFM systems, based upon a thorough physiological and ecological understanding of tree/root/weed competition for water and nutrients.

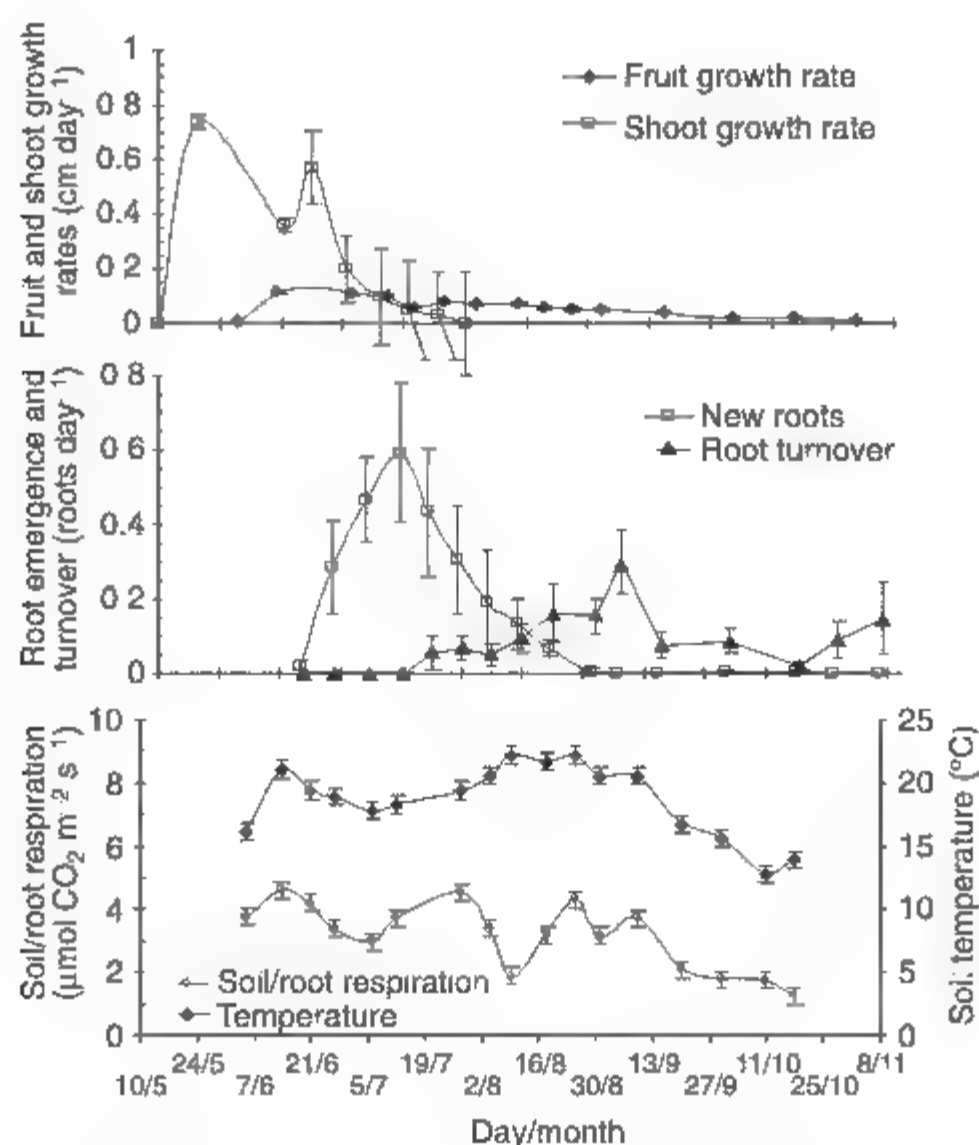


Fig. 13.2. Relative timing and rates of shoot and fruit growth, root growth and turnover, soil/root respiration rates and soil temperature beneath 4-year-old apple trees on M 9 rootstocks, under field conditions in a herbicide strip during one growing season (data from Psarras *et al.*, 2000)

Water and nitrogen are the essential resources most often implicated in competitive interference of weeds with fruit trees (Haynes, 1980). In studies of irrigation and nitrogen fertilization in orchards with different OFM systems, irrigation has often been more effective than nitrogen fertilization for promoting tree growth and yields (Hogue and Neilsen, 1987; Hipps *et al.*, 1990). Experiments with stable isotope ¹⁵N-labelled fertilizers have shown that soil nitrogen is more readily available to trees in herbicide-treated strips compared with turf grass, presumably because grasses have a relatively greater affinity for fertilizer nitrogen (Atkinson *et al.*, 1979). However, drip-irrigated apple trees in weed-free strips as narrow as 0.3 m surrounded by turf grass have grown and yielded as well as non-irrigated trees with or without added nitrogen in wider weed-free strips (Broeshart and

Keppel, 1985; Wijsmuller and Baart, 1988; Merwin and Ray, 1997). Early growth and yield of fruit trees in most reports have been lower in sod compared with herbicide-treated plots, and this has usually been attributed to water and nitrogen stress (Hogue and Neilsen, 1987). In a recent OFM study where microsprinkler irrigation provided supplemental water during periods of inadequate rainfall, yields of newly planted apple trees after the fourth year were not significantly lower in sod than in herbicide treatments, and the best cumulative yields occurred in post-emergence herbicide and woodchip mulch plots, despite the presence of considerable weed populations during most of the year in those treatments (Plate 13.2 and Fig. 13.3). These observations suggest that irrigation can reduce or compensate for weed interference in established apple plantings.

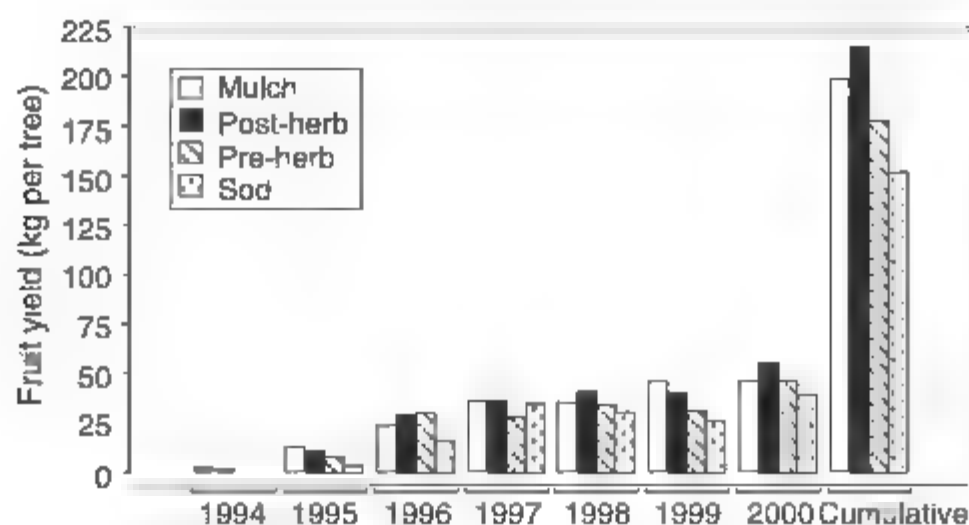


Fig. 13.3. Average and cumulative fruit yields over 7 years for trees in four OFM systems: hardwood-chip mulch (Mulch), post-emergence (glyphosate) herbicide (Post-herb), residual pre-emergence herbicides (Pre-herb), and a mowed sod grass (Sod). Repeated-measures analysis of variance (ANOVA) *P* values were 0.09 for treatments and 0.001 for time effects; data from an ongoing unpublished study of I.A. Merwin and I. Steenhuis.

In flood- or furrow-irrigated orchards, the movement and infiltration of water across and into the soil surface and the evapotranspiration of soil water reserves are affected substantially by OFM practices. Water evapotranspiration increased as much as 40% in California orchards with alleyway cover crops in comparison with completely weed-free herbicide systems (Prichard *et al.*, 1989). While surface flow is more rapid in weed-free systems, the sediment loads in irrigation tail water are also greater and water infiltration rates are reduced (Logan *et al.*, 1987; NRC, 1993). Soil-water consumption is greater in orchards with ground-cover vegetation and, without irrigation, soil-water availability is reduced substantially, even in regions with frequent rainfall during the growing season (Prichard *et al.*, 1989; Hipps *et al.*, 1990; Merwin *et al.*, 1994).

In summary, the interactions among fruit trees, weeds or ground covers and soil and water resources are affected substantially by OFM systems. Inadequate control of weed competition for limiting resources can have disastrous consequences for fruit growers. Although the complete eradication of weed competition is feasible with residual herbicides, it may not be necessary or desirable for economic and environmental reasons. Integration of weed- and soil-management tactics into comprehensive systems requires

knowledge and consideration of tree and weed root physiology and site-specific factors, as well as cost/benefit relationships and consideration of long-term ecological processes that determine the sustainability of orchard agroecosystems.

13.2 Contemporary and Traditional Roles for Orchard Ground Covers

Apples are often grown in cool humid regions of temperate latitudes, where precipitation occurs during much of the year. In such regions, it is often necessary to apply pesticides or fertilizers, prune trees or harvest fruit during inclement weather, when machinery traffic over wet soils can lead to compaction, rutting and erosion. To minimize such problems, perennial turf grasses are usually maintained between tree rows (Hogue and Neilsen, 1987). The densely matted root and shoot systems of turf ground covers help to protect soils from shearing and compression forces, reduce mud and debris on fruit and equipment and facilitate orchard management operations. In most apple orchards, permanent turf grass or seasonal cover crops are maintained in the alleys, despite the added costs of mowing or cultivation and potential for resource competition with the tree crop (Table 13.1).

Table 13.1. Important characteristics of grass and legume ground covers maintained on the orchard floor in apple-growing regions (from Heath *et al.*, 1985; Skroch and Shribbs, 1986; Hogue and Neilsen, 1987; Prichard *et al.*, 1989; Merwin and Stiles, 1994).

Ground-cover type	Nutrient use (N-P-K kg year ⁻¹)	C:N ratio	Water use	Establishment	Vigour	Durability
Red fescue (<i>Festuca rubra</i> L.)	60-80-40	40	Low	Very good	Low	High
Hard fescue (<i>Festuca duriuscula</i> L.)	50-80-40	40	Low	Good	Low	High
Tall fescue (<i>Festuca arundinacea</i> Schreb.)	50-60-40	50	High	Very good	High	High
Kentucky bluegrass (<i>Poa pratensis</i> L.)	70-80-40	35	Moderate	Good	Medium	Medium
Perennial ryegrass (<i>Lolium perenne</i> L.)	60-80-40	30	Moderate	Very good	Medium	Low
Annual ryegrass (<i>Lolium multiflorum</i> Lam.)	50-70-40	40	Moderate	Very good	High	Low
White clover (<i>Trifolium repens</i> L.)	10-80-60	16	High	Very good	Medium	High
Red clover (<i>Trifolium pratense</i> L.)	10-90-60	18	High	Good	High	Medium

The scenic beauty of many fruit-growing regions has made them important eco-tourism centres in Europe and elsewhere around the world. In such regions, fruit growers often benefit directly from agro-tourism, offering pick-your-own sales or bed-and-breakfast lodging for visitors. The aesthetic and ecological aspects of OFM systems are especially important in such situations, and some growers plant attractive cover crops or defer weed control during harvest or peak tourist seasons to make their orchards more pleasant to view, visit or harvest.

The high cost and limited availability of land suitable for fruit growing generate economic pressures to use that land intensively, hedging against price fluctuations or crop failures by multiple land uses or cropping systems. Polyculture – the simultaneous cultivation of several interspersed crop species on a single field – is rare in commercial orchards of Europe and North America, because it increases labour requirements. However, for diversified and subsistence farmers in regions where land costs are

more limiting than labour costs, it can be advantageous to intercrop orchards with vegetables, other fruit crops (e.g. strawberries beneath fruit trees), forage crops for hay or pasture and sheep or cattle grazing. Fruit-yield reductions from intercrop resource competition in such situations can be offset by the extra income from additional crops or usages.

In the past, orchards often served dual purposes for fruit growing and livestock grazing, hence pasture was the original OFM system in many regions (Morgan and Richards, 1993). With the advent of stringent cosmetic and phytosanitary standards, which require routine pesticide applications for fresh market apples, the use of orchards for livestock grazing has become less feasible. Still, in parts of France, Spain and England where apples are grown primarily for cider fermentation and the need for pesticide sprays is negligible, trees are high-budded on robust rootstocks and grass/legume mixtures are maintained throughout the orchard for livestock grazing beneath trees during much of the year.

Cover crops or crop rotations during orchard renovation and replanting can help to suppress problematic weed species and soil-borne pathogens that cause root disease and tree stunting (Mai and Abawi, 1981). Merwin and Stiles (1989) reported that pre-plant cover crops of 'Sparky' marigold (*Tagetes patula* L.) or 'Saia' oats (*Avena sativa* L.) suppressed lesion nematodes (*Pratylenchus penetrans* Cobb) and substantially increased the subsequent growth of apple seedlings in a New York orchard with severe replant disease. In Washington orchard soils, Mazzola and Gu (2000) observed substantial suppression of root disease and apple stunting, attributed to *Rhizoctonia solani* Sacc. AG5, following previous crops of wheat (*Triticum aestivum* L.). Other cover-crop species, such as Sudan grass (*Sorghum sudanense* Hitchc.) and mustards (*Brassica nigra* Koch and *Brassica juncea* Coss), have suppressed root pathogens of apple under laboratory conditions (Mayton *et al.*, 1996). Under field conditions in many New York orchards, the response of newly planted trees following purportedly disease-suppressive cover crops has been inconsistent and variable from site to site (Mai *et al.*, 1994; Merwin *et al.*, 2000). Using ground covers or pre-plant cover crops as alternatives to chemical soil treatments to suppress soilborne pathogens of apple trees remains a promising but unproved alternative (Pruyne *et al.*, 1994; Biggs *et al.*, 1997).

13.3 Practical Options for OFM

A combination of herbicide applications in the tree row and mowed turf in the alleyways has become the norm among apple growers worldwide. In this system, a continuous strip beneath the trees is treated with pre- or post-emergence herbicides to maintain a more or less weed-free area. This minimizes resource competition from weeds or ground covers by controlling their proximity to trees, and concentrates tree roots within the bare-soil strip, where they can proliferate and utilize the soil volume and fertilizers or irrigation more effectively (Atkinson, 1980). The optimal weed-free area in this system

depends on the soil fertility, availability of irrigation and age of the trees (Broeshart and Keppel, 1985; Hipps *et al.*, 1990; Merwin and Ray, 1997). In most situations, a single combined application of pre- and post-emergence herbicides provides sufficient weed suppression in the tree row throughout the year, making this the most economical OFM system (Merwin *et al.*, 1995). Alternatively, several applications of post-emergence herbicides (e.g. glyphosate) have also been shown to provide adequate control of weed competition in tree rows during the growing season, allowing a sparse ground cover to establish during the dormant season (see Plate 13.2) and providing some protection of the soil during the months when erosion and nutrient leaching are greatest in humid temperate zones (Haynes, 1980; NRC, 1993). Observations of nitrate-nitrogen in drainage water from OFM plots in an established orchard with grass lanes between different tree-row treatments have indicated relatively low nitrate leaching in orchards compared with other agronomic crop systems (Fig. 13.4), but nitrogen-leaching losses were usually greater in the herbicide treatments relative to mulch or sod-grass plots (Merwin *et al.*, 1996).

Soil-incorporated seasonal cover crops with herbicide strip systems are increasingly being used in fruit-growing regions with mild, wet winters and long, dry, growing seasons, such as California or the Mediterranean area (Elmore *et al.*, 1989; Prichard *et al.*, 1989). In this system, a weed-free strip is maintained in the tree row with herbicides or cultivation, and the alleyways are seeded with annual grasses or a naturally occurring cover crop is allowed to establish during the dormant season. This system facilitates irrigation and water infiltration during the summer months, maintains soil organic-matter residues, minimizes erosion during the dormant season and ties up (or fixes, in the case of legume cover crops) nitrogen and other nutrients during the winter when there is little uptake by the crop (Perret *et al.*, 1991; NRC, 1993). It has become increasingly popular in regions where nitrogen or phosphorus contamination of surface and groundwaters are problematic (Wein-

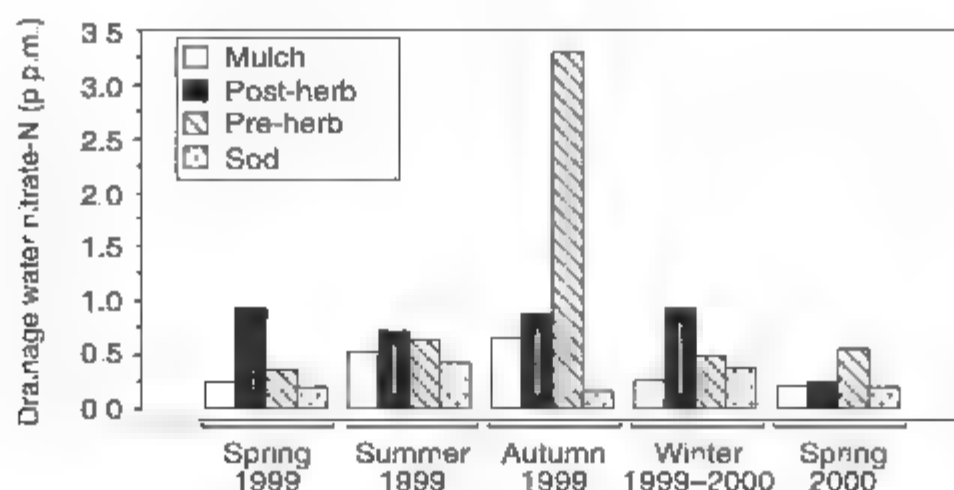


Fig. 13.4. Seasonal average nitrate-nitrogen concentrations (p.p.m. or mg N l^{-1}) in drainage water samples under four OFM systems in a mature apple orchard without nitrogen-fertilizer applications: hardwood-chip mulch (Mulch), post-emergence glyphosate herbicide (Post-herb); residual pre-emergence herbicides (Pre-herb), and a mowed sod grass (Sod). Data points are means of 12–36 water samples per season in each treatment, from an ongoing study described in Merwin *et al.* (1996).

baum *et al.*, 1992; Hornig and Bunemann, 1996a,b; Tagliavani *et al.*, 1996a,b; Gut *et al.*, 1997). In vineyards, this system has also been shown to increase the quality of grapes and the diversity and abundance of beneficial arthropods (Remund *et al.*, 1992), and similar benefits are likely in orchards.

The mulch-strip turf-grass alleyway system provides a practical non-chemical alternative to herbicide-strip systems. It involves applications of fabric, film or biomass mulches along the tree row to suppress weeds, and a mowed turf-grass or seasonally cover-cropped alleyway. For certified 'organic' growers, mulches are a preferred OFM system. Biomass mulches provide substantial quantities of organic matter, potassium, nitrogen and trace elements to the soil and indirectly to trees (Haynes, 1980; Hogue and Neilsen, 1987; Merwin and Stiles, 1994; Merwin *et al.*, 1994). They increase soil-water retention and availability, keeping the soil warmer in winter and cooler in summer, which may be advantageous in some regions. Weed species that thrive in cool, moist soils can eventually become a problem in biomass mulches, and may require supplemental control measures such as spot-spraying with herbicides or manual weeding. Populations of voles (*Microtus* spp.) and other rodents have increased under hay-straw, plastic film and fabric mulches, causing subsequent tree injury and yield losses (Byers, 1984; Merwin *et al.*, 1999).

On poorly drained soils in humid regions, prolonged water saturation of soil beneath mulches can increase the incidence of root and crown rots caused by *Phytophthora* spp., causing substantial tree mortality (Merwin *et al.*, 1992). Another disadvantage of mulches is their greater costs for establishment and maintenance compared with sod or herbicide OFM systems (Merwin *et al.*, 1995). Despite these problems, biomass mulches can provide an effective non-chemical system for reducing weed interference, conserving soil moisture and enhancing soil fertility in orchards.

Herbicide-treated bare-soil systems, in which surface vegetation is eliminated throughout the orchard, have provided the greatest long-term fruit yields in several studies (Robinson and O'Kennedy, 1978; Atkinson, 1980; Hipps *et al.*, 1990) and may be advantageous for irrigation or harvesting of tree fruits and nuts in some regions (Elmore *et al.*, 1997). Long-term use of certain residual or post-emergence herbicides on the entire orchard floor has promoted the establishment of herbicide-resistant moss (*Bryum argenteum* L.) or liverwort (*Marchantia polymorpha* L.) layers, which withstood traffic and were apparently non-competitive with trees (Robinson and O'Kennedy, 1978; Atkinson, 1980; Bastian, 1987; Merwin *et al.*, 1994). Cumulative yield increases of 20% have been reported where herbicides have been used over the entire orchard floor, com-

pared with herbicide strip/turf alleyway systems, but fruit quality (firmness, soluble solids and blush coloration) has often been reduced in comparison with herbicide strip or overall turf-grass systems (Plate 13.1; Hogue and Neilsen, 1987). Without surface-vegetation residues to protect the soil from rutting, crusting and erosion, overall herbicide treatment or cultivation systems are likely to cause long-term degradation of soil and water quality, and the trend in most regions is to avoid year-round overall herbicide systems in orchards (NRC, 1993).

Mechanical cultivation can be combined with herbicide strips or sod alleyways to provide weed control during the growing season or to incorporate dormant-season cover crops. In traditional plantings of large trees, it was often possible to plough or harrow in several directions parallel and perpendicular to tree rows, providing weed control over most of the orchard floor. The practice of clean cultivation was widely recommended and adopted during the early 1900s, but has been discontinued in most regions now for several reasons. Soil cultivation inevitably damages some tree roots, but, in deep soils or in regions where the upper soil layer is too hot during the summer for extensive proliferation of apple roots, it does increase tree growth and productivity compared with traditional sod orchards (Haynes, 1980). Continuous cultivation also reduces soil organic matter and structural integrity (Fig. 13.1), increases the potential for soil erosion due to exposure to water and wind and eventually leads to compaction and reduced soil fertility compared with no-till herbicide or sod systems (NRC, 1993; Merwin *et al.*, 1994). For these reasons, cultivation is often used in rotation with dormant-season cover crops, where the cover crops help to replenish soil organic-matter residues, reduce erosion and retain nutrients.

13.4 Ground-cover Vegetation Species, Types and Characteristics

The ground-cover vegetation in most orchards is a complex mixture of three types: grasses, legumes and broad-leaved

herbaceous perennials. In many regions, woody perennials, such as poison ivy (*Toxicodendron radicans* L.) and Virginia creeper (*Parthenocissus quinquefolia* Planch.), also occur and pose serious problems if allowed to proliferate beneath fruit trees. Such weeds must be rigorously suppressed with herbicides or manual weeding at first appearance, and are usually held in check by selective herbicides and routine mowing in the alleyways.

Each weed-control method selects over time certain ground-cover species with traits conferring resistance, tolerance or avoidance of that suppression tactic (Aldrich, 1984). With regular mowing over many years, a complex mixture of herbaceous ground-cover species develops in orchards, closely resembling cattle pastures in cool humid regions. In a New York study on a silty loam soil, intensive sampling of a regularly mowed orchard floor 1 year after renovation and seeding a turf-grass mixture of perennial ryegrass (*Lolium perenne* L.) and red fescue (*Festuca rubra* L.) revealed that more than 72 species were present within a 0.9 ha site, with ten predominant species each comprising at least 1% of total ground cover in all 50 sampled plots (Merwin, 1990). After 4 years under different OFM systems in that study (mowing, mulching, monthly cultivation and selective pre-emergence or broad-spectrum post-emergence herbicide treatments), distinct species mixtures had developed in each system. Herbicide-tolerant ground-ivy (*Glechoma hederacea* L.), pigweed (*Amaranthus retroflexus* L.) and milkweed (*Asclepias syriaca* L.) became dominant in pre-emergence herbicide plots. Mosses and weeds, such as dandelions (*Taraxacum officinale* Weber) and groundsel (*Senecio vulgaris* L.), with seeds dispersed readily during midsummer, infested sparsely the post-emergence herbicide (glyphosate) plots. In straw-mulch plots, weeds such as milkweed, couch grass (*Elytrigia repens* L.) and curly dock (*Rumex crispus* L.), which thrive in moist, nutrient-rich soils and produce persistent deep rhizomes or tap roots, became problematic after 4 years. In the frequently cultivated (rotavated) plots, couch grass, wild carrot (*Daucus carota* L.) and crabgrass (*Digitaria sanguinalis* (L.) Scop.) became

the dominant weeds. Elmore *et al.* (1989) and Skroch *et al.* (1975) have reported similar weed-species selection trends over time; each method of OFM selects for certain types of ground-cover species with distinct ecological and management characteristics. Rotation among different weed-management systems is an appropriate tactic for minimizing the adverse effects of system-related weed-selection processes.

Various types of grasses are seeded or occur naturally in orchards, including species with C-3 and C-4 photosynthetic traits, cool- or hot-season growth phases and erect, clumped or sprawling growth habits. A detailed description of common grasses is beyond the scope of this chapter, but many grasses are excellent ground covers for orchards (Table 13.1). Turf grasses, especially those of prostrate growth habit that spread by runners and/or rhizomes, are quite resistant to machinery and pedestrian traffic. Most orchard grasses have a high affinity for soil nitrogen and water (Hogue and Neilsen, 1987; Merwin *et al.*, 1994), with dense but relatively shallow root systems compared with fruit trees. Grasses do not usually serve as alternative hosts for virus diseases and arthropod pests affecting fruit crops, and they respond positively to routine mowing, forming a dense layer of thatch and turf that resists invasion by other herbaceous weeds. Low-stature cool-season grasses, such as red fescue or hard fescue (*Festuca durnuscula* L.) are preferred alley ground covers in many apple-growing regions, because they grow less vigorously and require less mowing during the midsummer season when nutrient and water stress are maximal for fruit trees. Seeding annual grasses, such as Italian ryegrass (*Lolium multiflorum* Lam.), may be useful in late summer to provide moderate nutrient stress, which improves fruit quality, reduces pruning costs and nutrient leaching and protects soil during the winter months (Tagliavani *et al.*, 1996a; Mantinger and Gasser, 1997).

Legumes, such as white and red clovers (*Trifolium repens* L. and *Trifolium pratense* L.), subterranean and strawberry clovers (*Trifolium subterraneum* L. and *Trifolium fragiferum* L., respectively), and vetches (*Vicia*

spp.) or alfalfa (*Medicago sativa* L.), are often grown in orchards for their soil-nitrogen contributions. Turf grasses often benefit from interspersed clovers, with the combination providing a more durable ground cover (Heath *et al.*, 1985). In California, strawberry and subclovers were reportedly useful orchard ground covers that provided soil protection and nitrogen inputs during the winter months and became dormant during the summer growing season (Elmore *et al.*, 1989). Until recently, clovers were recommended as ground covers in apple orchards of the eastern USA, but for numerous reasons legumes may not be desirable in apple orchards (Hogue and Neilsen, 1987). The uncontrolled release of nitrogen from legume roots and residues in late summer could reduce tree winter-hardiness and fruit quality, but there is little evidence that this actually occurs. Fruit damage from *Lygus* plant bugs (*Lygus lineolaris* L.) and the vectoring of graft-union necrosis virus into apple rootstocks are exacerbated with legume ground covers. The risk of honey bee poisoning increases greatly when insecticides are applied in orchards where legumes are flowering, and the relatively deep-rooted growth of most legumes increases their competition with trees for soil water and nutrients (Merwin and Stiles, 1994). For these reasons, apple growers often suppress legumes, using broad-leaved-selective herbicides such as 2,4-D (2,4-dichlorophenoxyacetic acid).

A multitude of broad-leaved herbaceous perennials occur in orchards, and most are treated as weeds and suppressed with herbicides or cultivation. Recent studies indicate that flowering ground covers that provide nectar, pollen or habitat for beneficial arthropods can increase the biological control of pests in fruit trees and vines (Remund *et al.*, 1992; Bugg and Waddington, 1994; Gut *et al.*, 1997). There is ample evidence that beneficial arthropod abundance and diversity are greater in orchards with flowering annual and perennial ground covers (Altieri and Schmidt, 1986), but little evidence that increasing beneficial populations in the understory results in significant levels of pest control

within the fruit and foliage of apple (Brown and Glenn, 1999). Further work is needed to quantify the trade-offs between potential biocontrol advantages and probable disadvantages, such as management complexity, resource competition between flowering ground covers and fruit trees and the risks for honey bees and other beneficial insects foraging on flowers during insecticide applications. Research in North Carolina and California has indicated that some ground-cover species are relatively non-competitive with fruit trees and can be promoted by selective management practices (Skroch and Shribbs, 1986; Elmore *et al.*, 1989). Fruit growers around the world are evaluating reduced-tillage and seasonal cover-crop systems as alternatives to clean-cultivation and residual-herbicide OFM.

13.5 Weed-control Methods and Equipment

13.5.1 Herbicide applications

Weed resistance to certain herbicides is a known problem in agronomic crops and a serious concern in fruit production, but at present there are effective herbicides available to control the major weed species in apple orchards (Derr, 2001). Tank mixing of selective herbicides and precisely directed spray applications enable growers to obtain sufficient control of weed competition in most circumstances (Tables 13.2 and 13.3). Various types and designs of herbicide sprayers are available, including shielded-boom sprayers, ultra-low-volume sprayers, wipers and backpack spot sprayers. Equipment is also available for

Table 13.2. Residual pre-emergence herbicides used in apple orchards. This list is for general reference only, and does not imply discrimination or endorsement by the author.

Dichlobenil	For hard-to-kill perennial weeds such as couch grass, nutsedge (<i>Cyperus esculentus</i> L.) and reduction of field bindweed (<i>Convolvulus arvensis</i> L.) Also effective for the control of annuals. Should be lightly incorporated in arid climates or applied in the rainy season for best results
Diuron	For annual broad-leaved plants and grasses or in combination with bromacil or other pre-emergence selective materials in some deciduous fruit crops
Napropamide	For annual grass control and in combination with other selective herbicides for broad-leaved plant control on young trees, because of its positional selectivity (surface adsorption and retention) above the root zone. If mixed down into soil, severe tree injury can occur
Norflurazon	For long residual annual grass and some broad-leaved-plant control. Sometimes used in combination with other selective herbicides
Oryzalin	For annual grass and some broad-leaved-plant control. Often used with other products to broaden spectrum of combinations. Applied around young trees and vines because of its relative safety for these plants due to positional selectivity
Oxyfluorfen	For a broad-spectrum broad-leaved-plant control material, often in combination with one of the grass-control herbicides, such as oryzalin, pendimethalin or napropamide. When used on young trees or vines, care should be taken to keep the spray off the foliage, or contact injury can result
Pendimethalin	For annual grass and some broad-leaved-plant control on young trees, often combined with other herbicides to enhance the long-term residual grass control
Pronamide	For annual and some perennial grass control, particularly couch grass
Simazine	For broad-spectrum control of annual weeds, especially effective on annual broad-leaved weeds and combined with other grass-control materials. Its long residual activity has made it a popular herbicide. Has been found in groundwater after long-term use in some locations
Terbacil	For long-lasting residual control of annual grasses and broad-leaved weeds in orchards
Trifluralin	For pre-plant control of grasses and some broad-leaved weeds. Applied as a continuous band under the soil surface, effective for the suppression of field bindweed in young plantings

Table 13.3. Post-emergence non-residual herbicides often used in apple orchards. This list is for general reference only, and does not imply discrimination or endorsement by the author

Fluazifop- <i>P</i> -butyl	Used for selective control of most annual and perennial grasses
Glyphosate	For selective control of most grass and broad-leaved species and woody weeds. Injury will occur if sprayed on to leaves or green bark of trees
Glufosinate	Primarily effective on annual grass and broad-leaved species, with less control of perennials
Oxyfluorfen	For control of young broad-leaved weeds, or in combination with other post-emergence herbicides
Paraquat	A non-selective contact herbicide used to control grass and broad-leaved annual seedlings
Sethoxydim	A selective herbicide for the control of most grasses, ineffective on broad-leaved weeds
Sulfosate	Non-selective herbicide for control of annual and perennial grasses and broad-leaved weeds. Selectivity based upon non-permeable woody outer bark of mature trees and vines
2,4-D	Used for selective control of most broad-leaved weeds. Care must be taken to minimize chance of drift on to leaves of crop plants, especially during warm weather

applying granular herbicides. In general, herbicides should be applied in a sufficient volume of water to wet a substantial portion of the surface area being treated, with minimal runoff. This often requires about 200–400 l of spray material per treated hectare, though substantially less may be needed with wiper or ultra-low-volume equipment. The optimal volume of water also varies with the herbicide being applied. For example, the effectiveness of glyphosate is often greater with lower volumes of water, while that of paraquat is improved by increasing the volume of water applied.

Sprayer application pressure should be kept low enough to minimize spray atomization in the nozzles and drift, but high enough to produce an even spray pattern in the nozzles and across the desired boom width. All sprayers should be carefully calibrated. Overdoses of herbicides can seriously damage fruit trees, while insufficient dosages may not provide effective weed control.

Shielded-boom herbicide sprayers, with shrouds or curtains between the crop and the nozzles, provide an extra margin of safety by minimizing drift, especially under windy conditions (Plate 13.3). Wipers are used to selectively apply herbicide to one portion of the ground-cover vegetation, with minimal chance for drift or penetration to the crop or desirable species in the ground-cover vegetation.

Backpack sprayers are useful where sparse or scattered weeds require spot treatment, but drift and inadvertent damage to trees is more likely with backpack applications.

13.5.2 Between-row cultivators

Various designs of rotavators and disc, brush, tine, rotary-hoe and chisel-tooth harrows are available for orchards. Mechanical cultivation usually provides only temporary weed suppression. Weed regrowth occurs after several weeks or months, depending upon ground-cover species mixtures and water availability. As many as six cultivations per season may be necessary to control weeds throughout the growing season, and perennial weed problems often increase when cultivation is the sole weed-control method.

13.5.3 Within-row cultivators

Many types of in-row cultivators are available and more are being developed and utilized as alternatives to chemical herbicides. Available equipment includes rotavators that swing in and out of the row; horizontal circular tillers that scuff soil out of tree rows, flat blades that cut under weeds; and the traditional hoe-plough, which turns a furrow

within the row and can be retracted in passing by trees. All of these implements work close to trees and can damage low-slung branches, trunks and shallow roots if improperly adjusted or operated.

13.5.4 Mowing equipment

Mowing is primarily done in the row middles of no-till orchards in older orchards in humid growing regions. There are mowers that cut within the row on trees or vines planted on level grades, but most work poorly in raised-bed or berm plantings. Available implements include rotary, flail and sickle-bar mowers. Some flail mowers are designed also to grind up tree prunings left on the ground in row middles, providing a thin mulch layer and retaining nutrients in the orchard. Flail and rotary mowers with side-delivery chutes can be operated to place the clippings as a mulch within tree rows, helping to move nutrients from the sod to the tree row and suppressing weed growth. Adjustable-width low-profile mowers are especially useful for season-long management of vegetative ground covers within the tree row, and they facilitate close mowing beneath trees with minimal damage to heavily cropped branches at harvest time (Plate 13.4)

13.5.5 Flame or steam weed suppression

Relatively little work has been done with flame or steam weed control in fruit planti-

ngs, due to problems such as air pollution, fire hazard and damage to the trunks and foliage of the crop. Preliminary work with in-row propane burners in apple orchards suggests that crop damage and fuel consumption can be minimized if the heat source is shrouded (Merwin and Ray, 1994; Plate 13.5). Flame or steam weed suppression is more short-term than contact herbicides, such as paraquat, but may be practical for organic and other growers who cannot use chemical methods of weed control.

13.6 Epilogue

There are many different systems for managing surface vegetation and soil resources in orchards, and each has its strengths and weaknesses. No single OFM system is best for all situations. Their relative merits are determined by soil and climate type, orchard age and design, grower preferences and resources, labour and capital availability, market incentives or 'green' labels, such as organic or integrated fruit production, and local regulations concerning soil and water quality. Moderate stress from managed weed competition at certain times of tree and fruit development may be preferable to total weed eradication that leaves the orchard soil without protective ground cover and prone to erosion and nutrient loss during much of the year. Ecological, environmental and economical factors must all be considered in developing OFM systems that improve orchard efficiency, enhance fruit quality and help to sustain vital natural resources.

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14 Pruning and Training Physiology

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14.1 Introduction

Pruning and training are almost always mentioned together, but there is a difference between them and each has a clear function. Pruning has been defined as the art and science of cutting away a portion of the plant for horticultural purposes. Pruning can be used to improve tree shape, to influence its growth, flowering and fruitfulness, to improve fruit quality, to repair injury, to contain the plant and to encourage light and spray penetration. Training, in contrast, refers to the direction of tree growth or form and the development of the structural framework of the tree. Pruning is only one of the techniques used in training. Although some training may be necessary after the tree comes into production, training is mostly confined to the period when the tree is becoming established. The ultimate goal of both pruning and training is to improve light distribution so that as much of the tree canopy as possible maintains production of high-quality fruit. Forshey *et al.* (1992) present a comprehensive treatise on pruning and training, including an extensive reference list. A comprehensive literature review will not be included in this chapter but references will be cited to illustrate key points.

Apple trees that are not trained and pruned become very large (Plate 14.1) and develop fine branching at the tree periphery, which becomes very dense and shades the tree interior. Fruit size, colour and sugar concentration decline on shaded spurs and, as light becomes still more limiting, the spurs themselves become weak and unproductive, eventually dying. As the trees age, a larger and larger portion of the tree canopy volume becomes unproductive. As the unproductive area of the canopy expands, it becomes a larger sink for photosynthates and thus decreases tree efficiency. The dense shading encourages insects and diseases due to high humidity, slow drying conditions and poor spray penetration. Thus, although pruning and training are expensive cultural practices, economic fruit production is not possible without the improvement in light distribution these techniques provide to maintain tree efficiency and fruit quality. The purpose

of this chapter is to provide the physiological basis for these cultural techniques so that they can be used to best advantage.

14.2 Pruning

14.2.1 Effects on growth

Although the practice of pruning goes back several thousand years, the science of pruning originated in the early 20th century, with experimental data revealing several general influences. The first of these is that pruning is a dwarfing process and the more severely a plant is pruned, the greater the degree of dwarfing. Removal of the branch not only removes stored carbohydrate and nitrogen reserves, but also reduces potential leaf surface and growing points as well. Obvious reductions in number of growing points, tree height and spread and leaf area can easily be observed on pruned versus non-pruned plants. Although not as obvious, pruning correspondingly reduces root growth, and new root growth will be delayed until shoot growth in response to pruning occurs.

There is a fundamental equilibrium between the above- and below-ground components of an apple tree. Removal of a portion of either the top or root system slows growth of the other until the balance is re-established (Taylor and Ferree, 1981; Geisler and Ferree, 1984a). This equilibrium is probably achieved not only through loss of reserves in the tissue removed, but also through changes in the functional equilibrium between the root and the top and the balance of hormones produced in meristematic regions in the leaves, shoot tips and root tips.

Shoot growth is dependent upon water and mineral nutrient uptake by the root system, while roots depend upon the above-ground portion of the tree for carbohydrates. Pruning away a portion of either of these plant parts reduces its capacity to perform its function; thus growth in other parts of the plant is reduced and energy is redirected to regenerate the missing component. This concept, known as functional equilibrium, seems to be moderated by plant hormones (Richards and Rowe, 1977).

Grochowska *et al.* (1984) have shown that pruning the top during the dormant season increases the supply of cytokinins from the roots, measured as increased concentration in the remaining above-ground tissue. These increased hormone levels are probably responsible for stimulating cell division and ultimately shoot growth, which, in turn, promotes auxin production in the shoot tips and gibberellin production in the new, unfolding leaves. The increases in concentration of these three classes of hormones found in shoot tissue in the early part of the growing season following dormant pruning not only increase growth but also alter the pattern of growth. Removal of terminal buds and their auxin results in enhanced growth of laterals of latent and existing flower buds. The more upright the branch that is pruned, the more vigorous will be the growth that responds to the removal of apical dominance (Myers and Ferree, 1983b).

Normally a terminal bud makes the most growth in an unpruned, upright branch, and each subsequent subtending lateral makes progressively less growth, until some form spurs, with the most basal buds not growing. This growth form is probably the result of cumulative auxin concentrations produced from each of the buds above causing a reduction in growth in the shoot originating at lower levels (Fig. 14.1). The classic

work of Verner (1955) illustrated that when four or more shoots were above a new branch, the angle of that new branch was $50-90^\circ$ (i.e. close to horizontal). When there were no shoots above the new branch, the branch angle was in the very narrow range of $0-40^\circ$ (i.e. very upright). Removal of the terminal bud results in an increase in the growth of the subtending laterals, and shoots that would have been spurs become vegetative shoots. Removal of apical dominance not only changes which shoots grow and their vigour, but the resulting shoots are more upright with narrower crotch angles. Thus, tree form is changed into a more upright, narrow shape.

Even though pruning dwarfs the whole plant or limb, an invigorating growth response occurs in the immediate area of the cut. This invigorating effect decreases as the distance from the cut increases. This is an important general concept to understand, because, if the purpose of pruning is to invigorate and stimulate growth, as is often the case in areas of the canopy that are spur-bound, more response is generated by many small cuts than by a few large ones (Ferree and Forshey, 1988). Generally, many small cuts stimulate more shoot growth, reduce fruiting to a greater degree and alter tree form more than when a few large cuts are made. Larger cuts result in fewer, more vigorous and more localized regrowth. Another manifestation of the localized influence can be observed in the injury that occurs when trees are pruned close to a sudden drop in winter temperature. The freezing injury results in death of the bark and phloem tissue and is most obvious close to pruning cuts, at the tree base and in limb crotches on pruned trees compared with unpruned adjacent trees (Rollins *et al.*, 1962; D.C. Ferree, personal observation). This localized response occurs even though the tree appears to be completely dormant.

One of the primary functions of pruning is to develop a framework of branches that are strong, likely to consistently carry a good crop of premium-quality fruit and be less prone to environmental extremes. To achieve this goal the crotch angle, which forms very early in the first year of the

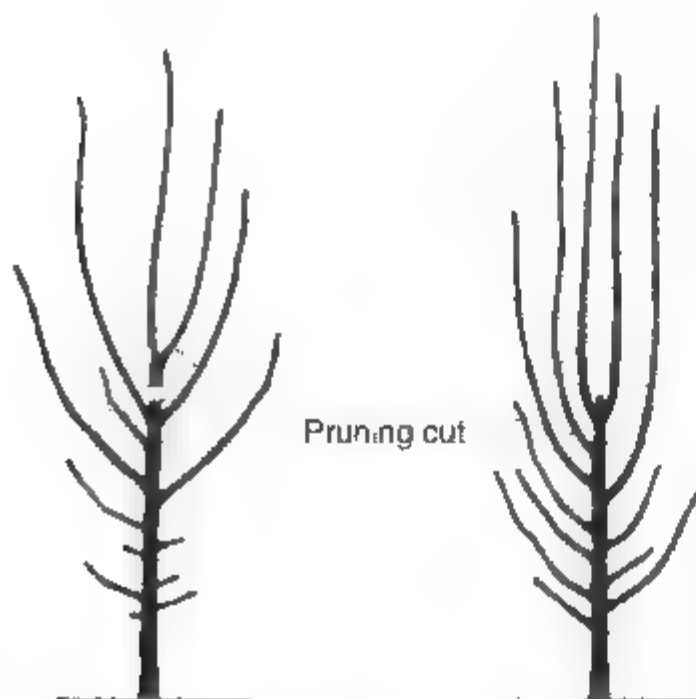


Fig. 14.1. Natural growth pattern of apple (left) and change in the pattern caused by a heading cut (right).

development of a branch, must be wide and strong. Narrow crotches cause bark inclusions, are weak, split easily and are more susceptible to cold injury. Wide crotch angles are formed naturally in very vigorous-growing trees that have very active meristematic areas that produce large quantities of auxin (Verner, 1955)

14.2.2 Effects on flowering

Another general principle is that pruning delays the flowering and fruit bearing of young trees and decreases fruiting in mature trees. Forshey *et al.* (1992) state that this is the result of the following three factors: (i) the removal of effective bearing surface; (ii) the stimulation of vegetative growth from growing points that were former or potential fruiting spurs; and (iii) direct competition between vigorous shoot growth and fruit set. They indicate that the reduction in cropping is proportionately much greater than the reduction in total growth. Pruning young trees tends to force growth of long succulent shoots, which continue to grow late in the season. Thus, carbohydrates do not accumulate for flower-bud initiation, but are used in producing the vigorous vegetative growth (Mika, 1975). Elfving (1990) demonstrated that heading back pruning in a single year significantly reduced tree size and yield and the effect remained evident 5 years after the pruning. The more severe the pruning, the greater is the decrease in fruiting (Elfving and Forshey, 1976). The negative influence of pruning on fruiting is particularly important in intensively planted modern orchards that are dependent on early cropping to help control growth.

14.2.3 Effects on fruit

One of the primary reasons for annual pruning is to increase fruit size. The effect on fruit size is not a direct effect of pruning, but results from the reduced number of fruit and improved light conditions in the canopy. Generally fruit set is higher on

pruned trees because the supply of reserves available to remaining blossoms is increased. Cell division early in the season is greater in areas of the canopy that have high light and large spur-leaf areas. Later in the season during cell expansion, shoot leaves supply the fruit. Fruit size is closely related to spur-leaf area and well-illuminated shoots (Ferree and Palmer, 1982; Rom and Ferree, 1986). Pruning is the cultural practice most influential in establishing a canopy light environment that promotes high spur quality and an even distribution of shoots through the canopy

14.2.4 Effects on mineral nutrients

Another indirect effect of pruning is the influence of pruning on the mineral content of the tree and fruit. The decrease in number of fruits caused by pruning is associated with an increase in leaf nitrogen, potassium and phosphorus and a reduction in fruit concentrations of magnesium and calcium. These changes are associated with the competition of the fruits and vigorous shoots for the elements and with the increase in fruit size caused by dormant pruning. Since calcium is so important to fruit storage potential and disorders such as bitter pit, the reduction in fruit calcium caused by pruning is a particular concern. Since vigorous shoots are a stronger sink for calcium than the fruit, dormant pruning reduces fruit calcium and the more severe the pruning, the greater the reduction. Dormant pruning also increases fruit size, which leads to a dilution effect on calcium concentration. In contrast, summer pruning, which removes vegetative shoots, can increase fruit calcium (Preston and Perrin, 1974).

14.3 Types of Pruning Cuts

All pruning cuts can be classed into two types (thinning out and heading back) and each type of cut produces a different physiological response. A thinning cut (Fig. 14.2) removes an entire shoot, spur, branch or limb, while a heading cut (Fig. 14.3) removes

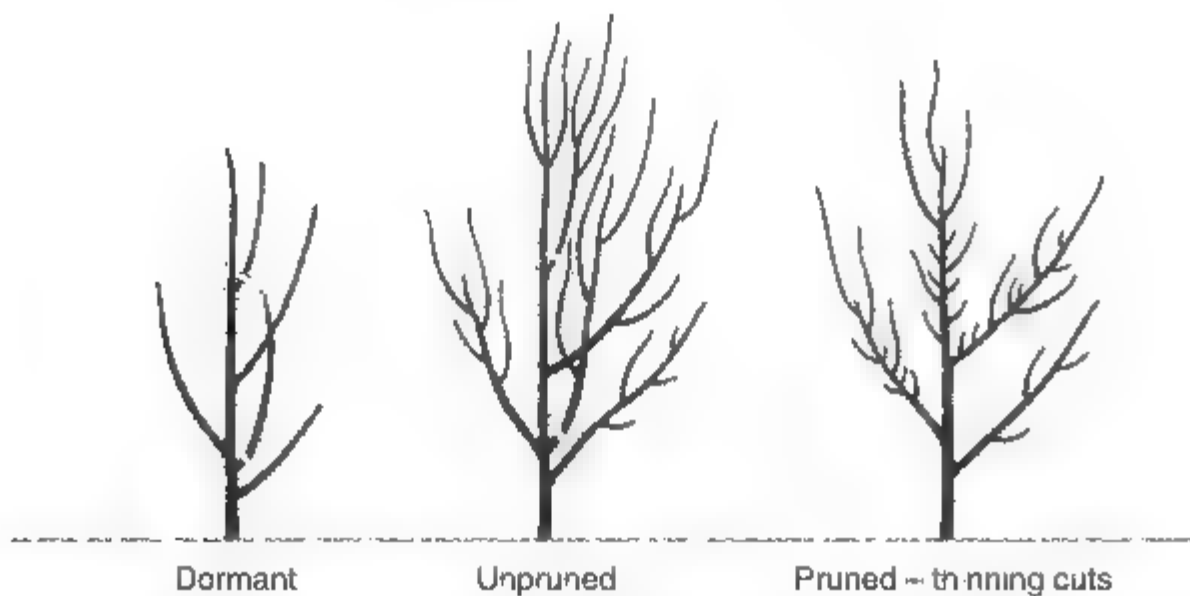


Fig. 14.2. Change in growth of an apple tree that received two dormant thinning cuts in year 1 (left-hand figure). Growth response at the end of year 2 is shown in the right-hand figure. The response for an unpruned tree is shown in the centre figure. In the latter case, main pruning cuts are needed in the second dormant season to restore a desired tree form but note that the advantages of lateral branch development and uniform fruit distribution have been lost.

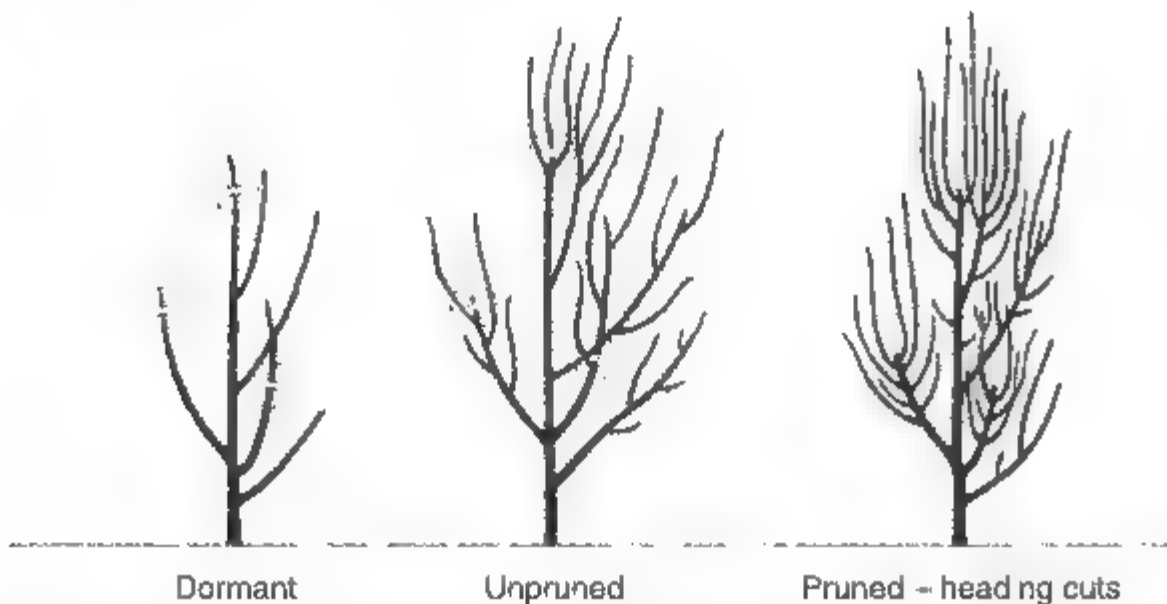


Fig. 14.3. Change in growth of an apple tree that received three heading-back pruning cuts in year 1 (left-hand figure). Growth response at the end of year 2 is shown in the right-hand figure where lateral branch development is strong and vigorous upright growth is apparent. The unpruned tree (centre figure) has a more spreading growth form with less lateral branching.

only a portion of a shoot or limb, leaving another portion from which new growth can develop. A comparison of the various responses from the two types of cuts is summarized in Table 14.1

14.3.1 Thinning cuts

Thinning cuts are primarily used to alleviate crowding and shading and generally improve light penetration into the canopy (Fig. 14.2). Thinning cuts also function to

remove unfruitful wood that is upright and vegetative or pendant and weak.

Generally, thinning cuts improve light distribution in the tree, thus increasing flower initiation, fruit set and spur growth in lower parts of the canopy. The effect of thinning cuts on fruiting is limited to the amount of potential bearing surface removed. The ratio of terminal to lateral buds is largely undisturbed and, by removing branches at their point of origin, only weaker latent buds are left to grow; thus, thinning out does not increase shoot growth as much as heading back.

Table 14.1. Relative influence of thinning and heading pruning cuts on apple trees.

Response	Thinning cuts	Heading cuts
Apical dominance	Little effect on remaining growth	Terminal removed, buds released
Shoot formation	Fewer vegetative shoots	Increased number and length
Spur formation	Increased	Decreased
Tree shape	Limited effect	Dramatic effect, e.g. hedging
Tree growth habit	Natural tall rangy	Compact and upright habit
Fruitfulness	Limited effect	Significant decrease
Carbohydrate reserves	Limited effect	Dramatic reduction
Nutrition elements	Limited effect	Decrease calcium, magnesium, increase nitrogen
Local stimulus	Encourage few shoots	Encourage many shoots

The thinning-out cut should be just above the small ridge at the base of a branch, called the collar. Cuts made at this location make the smallest wound, heal the fastest and are less susceptible to winter injury. Leaving a stub above the ridge or cutting too close and removing the ridge slows healing and provides more potential for disease or insect damage (Shigo, 1990). An exception to this rule is the Dutch cut, a bevelled stub that is left for stimulating a renewal limb with certain training systems (see Chapter 15).

14.3.2 Heading cuts

Heading cuts (Fig. 14.3) locally stimulate more vegetative growth, which tends to be vigorous and shades the tree interior, resulting in fewer fruiting sites and less flower initiation than thinning cuts. Since using this type of cut removes many terminal buds, apical dominance and the hormone balance is disturbed more than with thinning cuts. Heading increases both shoot number and length, but the effect on length is determinate. The younger the wood and the more upright the growth headed, the greater the effect. Heading 1-year-old wood results in a strong localized response, releasing the three to four buds below the cut to develop into vigorous, upright shoots with narrow crotches. Heading causes many shoots that would have been potential spurs or fruiting shoots to form vigorous vegetative growth. Elfving (1990) has shown that heading cuts on young trees have negative effects on

growth and fruiting lasting 5 years. Heading cuts stiffen limbs and care should be exercised in the use of these cuts on upright branches of young trees because some type of physical limb bending will be required to return these branches to a balanced fruiting condition.

Each type of cut has a role in creating and managing an efficient tree with a good balance between vegetative vigour and fruiting. Newly planted trees are headed to stimulate the production of strong lateral branches needed to form scaffolds. Thinning cuts are necessary on young trees to develop the desired primary branch framework with minimal effect on fruiting. As trees reach full size, thinning cuts maintain the adequate light and spray penetration needed to keep the whole canopy productive, while fruit size and quality are improved. Cultivars such as spur-type 'Delicious' often form insufficient numbers of laterals and may benefit from heading cuts to induce laterals where they are needed. In older trees, when portions of the canopy become weak or spur-bound, heading cuts can encourage shoot growth and improve fruit size.

14.4 Time of Pruning

Most pruning on apple trees is done when they are dormant. In areas that can experience very low temperatures in winter, time of pruning is an important consideration because it increases susceptibility to low-temperature injury (winter injury). Sensi-

tivity to cold injury after pruning is greatest in the tissue in close proximity to the pruning cuts. The exact temperature required to induce winter injury varies with many factors, such as previous exposure to low temperatures, previous crop, cultivar, rootstock and tree age. Winter injury may occur at low temperatures in the range of -23 to -49°C , depending upon the inherent hardiness of the tree and these contributing factors. Pruning within 2 weeks prior to the low-temperature event will increase the sensitivity of the tree to cold injury, with the greatest loss of hardiness occurring within the first 48 h (Rollins *et al*, 1962). The loss in hardiness is then gradually regained. Thus, the risk of causing winter injury by pruning can be reduced by suspending pruning work when severe cold weather is forecast (see Chapter 10).

To reduce the risk further in areas prone to winter injury, pruning should be delayed, where practical, until after the coldest months (January and February in the northern hemisphere). If pruning must be started earlier, it is best to prune the oldest trees and most cold-tolerant cultivars first and to delay pruning the youngest trees and most cold-sensitive cultivars.

When pruning is delayed until growth starts, the tree responds differently. Delay much beyond bloom devitalizes growth and may interfere with the development of flower buds for the next year's crop. Pruning cuts at the time vegetative growth is beginning result in an increase in the number of buds that break and buds further from the cut tend to break more when compared with dormant pruning. This response is probably due to the removal of apical dominance since the meristematic regions in the growing buds are primary sources of auxin. Generally the breaks that occur from delayed pruning are less vigorous and may be very desirable on cultivars that tend to have blind wood (previous-season wood with no lateral growth), such as 'Tydeman's Red' or 'Rome Beauty'. Delaying dormant pruning until bloom can also be used to lessen the regrowth in overly vigorous trees; however, delayed pruning should not be used on trees with less than optimum vigour.

14.5 Pruning Trees of Different Ages

14.5.1 Young trees

Most apple orchards are trained to some modified form of a central leader system, resulting in a cone-shaped canopy. In this tree form, the central stem, or leader, is maintained in an upright orientation, while limbs that form on the sides are trained at an angle to form the primary scaffolds. Additional secondary limbs form on both the leader and the scaffolds and are maintained to provide a bearing surface. The purpose of this chapter is not to provide a 'how-to' treatise on pruning trees trained to specific systems, but to cover the principles and physiological basis for practical application for a generalized central-leader system. The specific alternative pruning practices for young trees in specific training systems will be covered in Chapter 15.

Trees that come from the nursery have lost a significant amount of their root system and thus the top needs to be reduced to create a balance so that sufficient growth occurs to form the permanent scaffolds. If trees arrive as unbranched whips, they are usually headed back 60–90 cm above the ground, depending on which training system is used. Cultivars such as spur-type 'Delicious' do not branch easily and will only produce shoots within 5 cm of the heading cut, while cultivars such as 'Golden Delicious' will produce more laterals, which are distributed 10–15 cm below the cut (Ferree, 1978). Cultivars that have a terminal bearing habit should be headed high, as these cultivars tend to produce weaker shoots from the lower buds, plus the terminal bearing habit causes the branches to bend, which can cause them to interfere with herbicide applications and mowing operations if they originate too low on the trunk.

If feathered trees (see Chapter 6) are planted, shoots to form the primary scaffolds are already in place and, generally, the only cuts made on these trees are to remove any spurs or shoots below 45 cm above the ground, as these interfere with weed control and will produce few marketable fruit.

During the first growing season, leader and scaffold selection are very important and should be done early so that the tree directs its growth as much as possible into tissues that are to be retained. Each growing shoot produces auxin, which moves down the tree and affects the growth and crotch angle of shoots below. The uppermost shoots grow vertically because of an absence of auxin during and after bud break. The progressively increasing auxin concentration further down the trunk stimulates lower shoots to develop wider crotch angles and this effect is complete by the time the shoots are 5–10 cm long (Verner, 1955). This natural pattern can be used to advantage by selecting the leader when the shoots are 10 cm long, removing the two or three upright shoots that are growing just below the leader and leaving the lower shoots with wider crotch angles to develop as scaffolds. Since the tissues in question are succulent, care must be exercised to avoid injury to the vascular tissue, as this can decrease the growth

of the remaining leader shoot. Cultivars such as spur-type 'Delicious' may not produce sufficient shoots to use this method of leader selection. In this instance, the shoots with upright growth and very narrow crotch angles, which would be removed in the above procedure, are retained. A spring clothes-peg is clamped around the leader just above the young shoot when it is 5 cm long, and it is forced to grow horizontal below the clothes-peg (Fig. 14.4). This shoot will ultimately curve upward, but only after a wide, strong, crotch angle has been established. The growth of these shoots is reduced 15–20% by the bending process further establishing the dominance of the leader. An alternative to the clothes-pegs is to use pointed toothpicks or thin wire to force the new shoot to grow laterally. These practices must be carried out before the base of the shoot lignifies. It takes about 1 min per tree to install the clothes-pegs and about 15 s to remove them 3–4 weeks later to avoid girdling the leader.

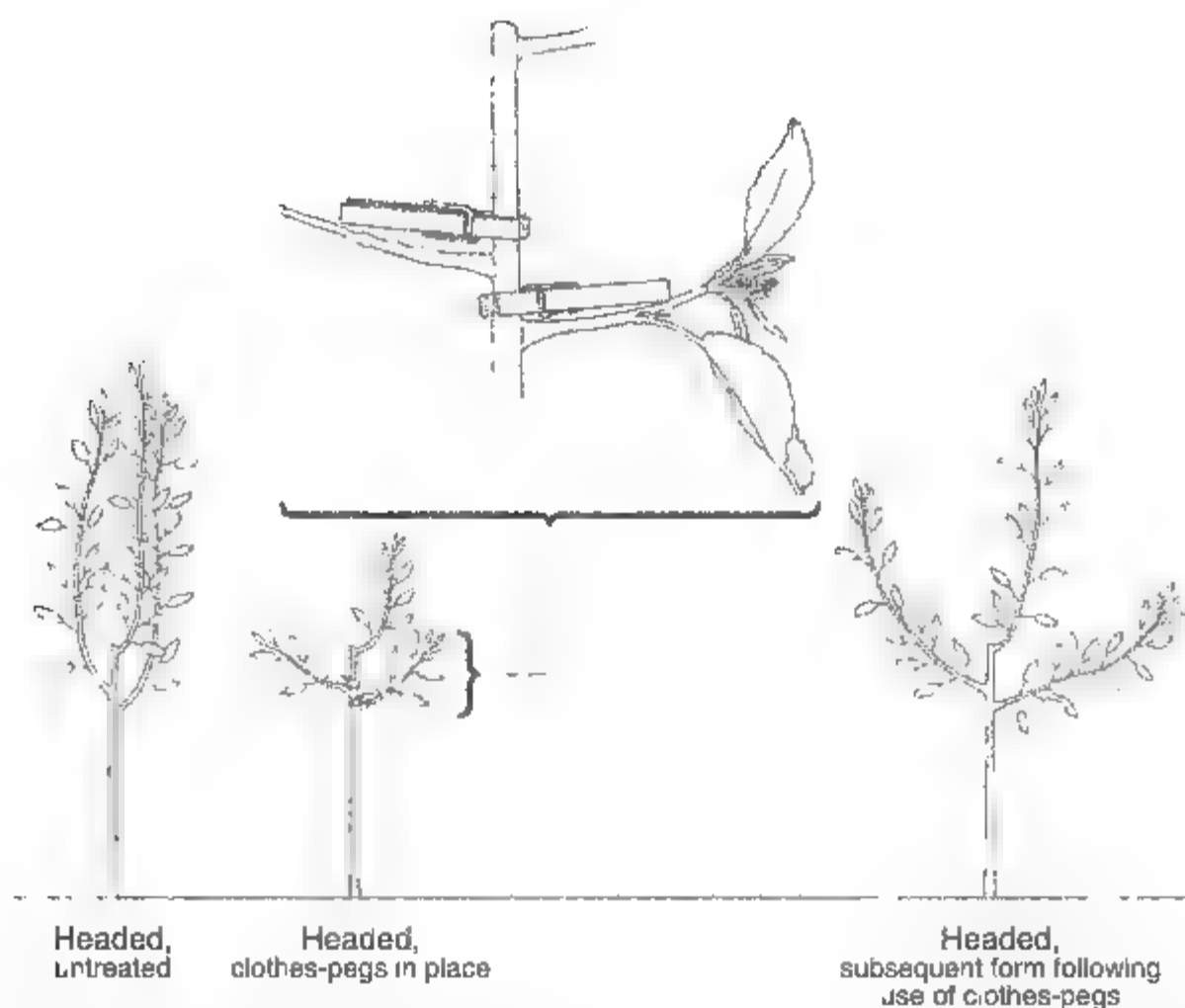


Fig. 14.4. Influence of clothes-peg spreading on growth of a newly planted unbranched apple tree that has been headed.

The most important principle to remember on young trees is to prune them as little as possible. The delay in cropping caused by heavy pruning has an adverse effect on early profitability. In intensive plantings the vigorous growth caused by heavy pruning may negate much of the advantage in early yields that are achieved by using increased tree numbers.

14.5.2 Fruiting trees

Although young trees are often handled similarly, as the tree begins to fruit, pruning practices must be adjusted to the vigour of the cultivar and rootstock (see Chapter 5) and the growth and fruiting habit of the cultivar. Tree vigour is influenced by many factors. Fertile, well-drained soil results in much greater vigour than shallow, poorly drained soil. Some climates are ideal and promote vigorous growth, while others cause stresses that reduce growth. Cultural practices, such as nitrogen fertilization and weed and soil management, influence growth. All these factors interact with the genetic potential of the scion and rootstock and must be considered when judging the responses of the fruiting tree to pruning

Vigour varies throughout the canopy, with greatest vigour in the top and periphery. This variability is mostly due to light exposure and one of the main goals of pruning is to create the optimum balance of vigour and fruiting in as much of the canopy as possible by improving canopy light distribution. The orientation of fruiting branches affects vigour and relative response to pruning (Fig. 14.5). Normally upright branches are mostly vegetative and respond to pruning by growing vigorously. It is best to remove these by thinning cuts to avoid shading portions of the canopy below them. Pendant branches are often weak and have low fruit set and poor fruit size, colour and quality (Tustin *et al.*, 1988). These branches should be removed to eliminate the small, low-quality fruit they produce. Branches with an orientation between horizontal and 45° above horizontal are the most fruitful, have the highest fruit quality and should form the greatest portion of the fruiting canopy. Even distribution of light across these branches is maintained by thinning-out cuts.

Cultivars respond differently to pruning and training due to differences in their overall level of vigour, growth and fruiting (Table 14.2). Growth habit refers to the overall growth pattern of the tree, including the degree of branching, the branch orientation

Fig. 14.5. Influence of branch orientation on growth and fruiting of apple

Table 14.2. Relative vigour of some commercially important apple cultivars and their growth and fruiting habit according to Lespinasse (1980).

Low vigour	Medium vigour	High vigour
'Braeburn' (II)	'Cox's Orange Pippin' (III)	'Cortland' (IV)
'Idared' (II)	'Delicious' (II)	'Granny Smith' (IV)
'Jonathan' (III)	'Elstar' (II-III)	'Gravenstein'
'Rome Beauty' (IV)	'Empire' (I)	'McIntosh' (III)
'Spur Delicious' (I)	'Fuji' (IV)	'Mutsu' (III)
'Spur Golden Delicious' (I)	'Gala' (III)	'Northern Spy' (II)
'Spur McIntosh' (I)	'Golden Delicious' (III)	'Spartan' (II)
'Tydemans Red' (IV)	'Jonagold' (II)	

(upright or spreading) and the branch crotch angle. Fruiting habit refers to the overall pattern of fruiting and includes fruit position on the ends of long or short shoots, age of spurs producing most of the crop and location of the crop on the scaffold limbs. Lespinasse (1980) developed a system of classification for growth habits (Fig. 14.6) and these have strong implications for the type of pruning required.

Spur types, characterized by spur strains of 'Delicious', are classified as Type I. These tend to form few laterals on main scaffold limbs and have strong basitonic characteristics (the most vigorous growth is at the base of the tree). Thus the pattern of growth in type I cultivars is characterized by strong scaffold limbs breaking at the base of the tree. The dominance of the central leader is lost quickly unless shoots intended as scaffolds are mechanically spread to weaken their growth relative to that of the leader. Heading cuts may be needed to develop lateral branches on primary scaffolds, which forces would-be spurs to grow into vegetative extension shoots. Due to the sparse branching habit more scaffolds may be left, but care must be taken that they are spread vertically along the leader or the dominance of the leader and its growth will be reduced. Fruiting occurs on numerous short spurs, which are long-lived. The zone of fruiting remains close to the trunk and to the base of the scaffolds as long as sufficient light is maintained in these canopy areas. Type I cultivars tend to be prone to biennial bearing and can easily become spur-bound and senescent, particularly if they are propagated on very dwarfing rootstocks.

Type II is characterized by standard-habit 'Delicious'. Branching is more frequent than in Type I and there is a tendency for the fruiting zone to move away from the trunk. The trees have a tendency to develop narrow crotch angles and benefit from spreading. Type II trees may develop many medium-sized branches, resulting in a too dense canopy if not thinned out. No more than four permanent branches per tier should be retained. More thinning cuts into younger wood are required to induce spurs and retain the fruiting zone in the tree interior.

Type III cultivars are characterized by 'Golden Delicious' and tend to be spreading with wide crotch angles and frequent branching. Cultivars of this type tend to bear early, with most of the fruit on spurs or terminals of short shoots borne on 2- to 4-year-old wood. The fruiting zone on cultivars in this classification tends to move away from the trunk to the outside of the canopy. This requires thinning on the canopy periphery and heading cuts to lateral branches on the bases of scaffolds to induce renewal of fruiting wood. Trees of this type are the easiest to adapt to a wide range of training systems and are generally the easiest to manage in the orchard.

Type IV, the tip bearers, are characterized by 'Rome Beauty' and 'Granny Smith'. They tend to have upright main scaffold limbs with narrow crotches and frequent branching. A weeping terminal habit develops since most of the crop is produced on the ends of the previous year's shoots. The lower half of many shoots will be devoid of leaves or fruit on young trees, a condition known as 'blind

Fig. 14.6. Lespinasse (1980) classification of apple-cultivar growth habits.

wood'. Delayed spring pruning can often induce laterals in this branch region, which would normally be bare. This growth habit tends to be the most annual in production and is often associated with high productivity and large fruit size.

Low-vigour cultivar-and-rootstock combinations can be pruned harder than high-vigour combinations without upsetting the balance of growth and fruiting. Some rootstocks, such as Oregon 1, cause upright growth, while others, such as M.9 or M.9 interstems, cause an open-spreading canopy. Rootstocks that promote an open-spreading canopy combined with cultivars with little tendency to maintain a central leader, such

as 'Empire', require special treatment during the developmental years if they are to be successfully grown and managed in training systems that depend on a defined leader.

In a young fruiting orchard, leader management and, ultimately, tree height require consideration. As planting density intensifies, it is critical that one row of trees does not shade the adjoining row. Several studies show that a north/south orientation results in more even canopy light distribution. In model studies (Cain, 1972; Palmer, 1989) it has been shown that tree height should not exceed twice the clear alley width. If a 2.5 m free alley is needed for spray equipment and removal of fruit at harvest, then trees should

not exceed 5 m in height. If this is exceeded, much of the row will be shaded in the afternoon by neighbouring rows

In-row spacing also has an impact on leader management. Tustin *et al.* (1998) have shown that creating rows with a sawtooth profile from creating a gap between leaders of adjoining trees results in improved light distribution and improved fruit quality. To achieve these goals there must be strong vigour in the leader when the trees are young. This is achieved by removing shoots competing with the leader. In cultivars such as 'Empire' that fail to develop strong leaders, the leader should be headed by a third each year and then singled to one shoot early in the growing season. When the tree reaches the desired height, the leader can be cut back to an upward-growing shoot each year, just below the desired height, and the competing shoots removed. In supported systems it is possible to let the leader fruit and bend over and after fruiting cut to one upright shoot and repeat this process every couple of years. Handling tree height in systems such as the slender spindle, which requires a weak leader, or systems that have more than one leader is covered in Chapter 15

Some very large orchards attempt to reduce the cost of pruning by mechanically hedging or pruning only every second or third year. Mechanical pruning unfortunately causes mostly heading cuts, and the vigorous upright shoot growth that follows quickly produces heavy shade in the tree, which reduces flower formation and fruit quality. This effect is particularly bad if follow-up manual pruning is not used to thin out the tree periphery and allow light penetration to the canopy interior. Even with annual follow-up hand-pruning, mechanical hedging, although successful in maintaining tree size, has not been economic in maintaining yield and fruit quality (Ferree, 1976b, Ferree and Lakso, 1979; Ferree and Rhodus, 1993). In a comparison of pruning six cultivars annually with limb spreading compared with every second or third year without spreading, it was found that the annual treatment gave the highest absolute return per tree (Ferree and Lakso, 1979). Thus, although pruning is a costly practice, the cost is justi-

fied on young fruiting trees and the indiscriminate cuts from mechanical hedging generally result in uneconomic production.

14.5.3 Old or declining trees

As trees age, fruit size generally declines and it requires a more detailed and time-consuming pruning job to achieve adequate fruit size and quality. Trees can become spur-bound and perform as old trees even though they are not old (Ferree and Forshey, 1988). These trees often have very large spur complexes with many weak growing points and have very little shoot growth in the lower portion of the canopy. Spur pruning that removes 30% of the growing points on each spur complex, plus a series of heading cuts over the canopy can improve fruit size in these trees.

Another problem common in older orchards is that too many limbs have been allowed to develop in the top of the trees. The upper limbs in the tree shade the lower limbs, and this uneven light distribution limits production and fruit size in the bottom half of the canopy. Often the productivity and profitability of old trees are limited by being both top-heavy and spur-bound.

A comparison of several corrective pruning strategies for top-heavy, spur-bound 'Starkrimson Delicious' trees showed that removing several large limbs in the top of the canopy or making numerous heading cuts improved light penetration, improved fruit size and increased fruit quality, but the reduction in yield in these treatments resulted in no economic benefit (Ferree *et al.*, 1990). Spur pruning produced the smallest increase in fruit size, but also reduced yield the least, resulting in the greatest cumulative yield and economic value. The outcome of this study was due in large part to the amount and severity of cuts that had to be made to achieve the desired canopy shape. Converting older trees to canopy shapes that improve light distribution, such as the palmette leader (Lakso *et al.*, 1989), can be done with less loss of yield when starting with a well-structured central-leader tree (Warrington *et al.*, 1995).

If trees have been neglected and not pruned for several years, it is best to make several large thinning cuts, removing limbs to open the canopy. It is critical not to prune too excessively in the first year. A few large cuts will allow adequate light penetration to stimulate fruiting wood lower down in the canopy. In the second and third year, a gradual thinning of the canopy should be done, with the focus on renewing the bearing surface by favouring the retention of young limbs over old ones. If trees have been neglected for more than a couple of years, it is generally not economical to return them to commercial production. Thus, an economic comparison must be made before deciding whether to prune or to remove old or neglected trees

14.6 Summer Pruning

Although summer pruning has been used for several centuries in some European orchards, the practice was never widely adapted until more recent times. Saure (1987) published a comprehensive review of the many studies evaluating the impact of the practice on the growth and fruiting of apple

14.6.1 Effects on physiological processes

Summer pruning affects several of the basic physiological processes of apple trees (Ferree *et al.*, 1984). Photosynthetic rates of basal leaves remaining after trees were summer-pruned were 11–39% higher than corresponding leaves on unpruned trees. These rates were equivalent to those in much younger leaves on unpruned trees. As summer-pruning severity increased, the delay in decline in photosynthesis increased. This delay in the decline of leaf performance was similar to the response induced by increased cytokinin levels. Since the root system of the summer-pruned trees was not immediately affected, it might be expected that the root system would continue to produce the same quantities of cytokinins as it did prior to pruning, thus increasing the supply to the remaining leaves. Evidence indicates that the

effects of summer pruning on apple are not controlled by carbohydrate levels or by the type of carbohydrate present (Taylor and Ferree, 1986). A redistribution of carbohydrates does occur in response to summer pruning and is probably controlled by the removal of the buds and/or growing points (Saure, 1987).

Quinlan and Preston (1971) showed that repeated pinching of a growing bourse shoot modified the distribution pattern of assimilates. Movement of photosynthates out of the primary leaf towards the growing shoot tip was shifted by the pinching to mainly basipetal transport toward the flower clusters and the fruitlets, which is the normal direction of transport after terminal bud formation. A similar shift in assimilate distribution may be responsible for increased fruit set and improved spur quality in the canopy interior in response to early-summer pruning

14.6.2 Effects on fruits

Summer pruning has been used primarily to improve red fruit colour and fruit quality, while attempts to control growth by summer pruning have been less successful. Many studies show a dramatic improvement in red fruit colour of difficult-to-colour cultivars, such as 'McIntosh' and 'Gala' (Lord and Greene, 1982; Warrington *et al.*, 1984); however, the red colour of cultivars that have a high colour factor, such as the red strains of 'Delicious', is often not affected. Summer pruning often improves storage quality by reducing bitter pit, internal breakdown and water-core (Preston and Perrin, 1974; Myers and Ferree, 1983a). The reduction in these storage disorders is probably related to the increase in fruit calcium that results from summer pruning (Table 14.3). Fruit calcium is enhanced by summer pruning early, before terminal bud formation and during the time of active cell division in the fruit, while pruning after terminal bud formation has little effect on fruit calcium concentrations. The increase in fruit calcium resulting from summer pruning can often overcome the adverse effect on fruit calcium induced by reduction of crop due to frost or excessive growth from

Table 14.3. Effect of summer pruning for 3 years on growth and fruiting of 'Jonathan' apple (from Taylor and Ferree, 1984)

	Trunk area (cm ²)	Canopy openness ¹ (% sky)	Marketable fruit (%) diameter (cm)			Firmness (kg)	Colour rating ²	Water- core ³
			> 8.0	8.0–7.3	7.3–5.7			
Control	168a	14b	3.8b	28.8b	65.1a	6.86b	3.8b	0.38b
Summer-pruned	148b	28a	12.7a	48.9a	37.9b	6.98a	4.0a	0.54a

¹ Measured by fish-eye lens at tree base² Colour rating: 1 = green to 5 = full red³ Water-core rating: 0 = no water-core to 5 = severe water-core throughout cortex.Values with letters uncommon are statistically different ($P = 0.05$).

dormant pruning, but the increase is not adequate to overcome a general calcium deficiency. If too many shoot leaves are removed in summer pruning, fruit size can be reduced, as well as fruit soluble-solids concentration. Modest summer pruning can achieve the increase in fruit colour without adverse effects on fruit size and soluble solids; thus, these factors must be closely monitored to avoid negative effects.

Although early reports indicated that flowering and fruit set were enhanced by summer pruning (Saure, 1987), most recent work shows either no effect or reductions. Heavy summer pruning occasionally causes some buds to break into growth and flower late in the season, so that bloom and ripening fruit exist at the same time on trees. This is more prevalent on some cultivars, such as 'McIntosh' and 'Jonathan', and the inflorescence is often extended rather than compact. Likewise, the influence of summer pruning on fruit set and fruit abscission is unclear, with studies reporting contradictory results. Since all of these factors influence yield, it is not surprising that the reports of the influence of summer pruning on yield are variable.

14.6.3 Effects on growth

Results on container-grown apple trees indicate that shoot growth, leaf area, stem diameter and root growth are reduced by summer pruning (Plate 14.2; Taylor and Ferree, 1981). Summer pruning has been advocated as a method of devitalizing very

vigorous trees that exceed their allotted space. Generally, summer pruning is conducted on the periphery of the tree removing vigorous growth by cutting to the bud-scale scars or to the first spur on 2-year wood. Growth produced the year following summer pruning has been equal to growth from dormant pruned trees (Myers and Ferree, 1983b). Marini and Barden (1982) found no difference in growth, if vigorous trees were pruned identically, either while dormant in winter or while growing in summer. Forshey *et al.* (1992) indicate that moderate summer pruning may have little practical benefit for vegetative vigour, even if repeated over several years. They indicate that summer pruning sufficient to reduce vegetative vigour is usually accompanied by reduced yield, fruit size and/or fruit soluble-solids concentration and may also produce significant negative side-effects in flowering and winter-hardiness. Thus, any benefit of summer pruning in controlling growth is temporary and must be coupled with other techniques and management practices to achieve a desirable balance of growth and fruiting

14.6.4 Practical implications

In reviewing the research on summer pruning, several principles evolve that have practical significance (Table 14.4). Pruning early, before or just after terminal buds form, can increase current-year fruit set by reducing competition from rapidly growing shoots.

Table 14.4. Summary of the influence of summer pruning on the growth and fruiting of apple trees.

Characteristic	Increased	Decreased	No change
Leaf photosynthesis	X		
Leaf carbohydrates			X
Fruit calcium	X		
Fruit colour	X		
Bitter pit		X	
Water-core		X	
Fruit size		X?	
Fruit soluble solids		X?	
Late-season flowering	X		
Growth following season			X

Pruning at this time will also result in vegetative regrowth in close proximity to the cut and the earlier in the season the pruning is done, the greater will be the vigour of the regrowth. Regrowth in the current season is reduced or eliminated if summer pruning is performed 1–2 months before harvest but after terminal buds have formed. Regrowth in the current season is also reduced as cuts are made into older wood. Cuts made to the first spur bearing fruit on 2- or 3-year-old wood often do the most to open up the canopy and promote improved fruit colour, without undesirable current-season regrowth. Removal of entire shoots by thinning cuts produces little or no regrowth when done after terminal-bud formation. Because the remaining sites of auxin production are undisturbed, little disruption of the apical-dominance control system occurs. This approach provides the maximum improvement in fruit colour since it allows more light to reach the fruit.

Although the primary use of summer pruning is on fruiting trees to improve fruit colour and quality, there are several other uses that are beneficial. Removal of water sprouts in the tree centres and on major scaffolds of older trees improves light and spray penetration and reduces problems from some insects. Water-sprout removal can be done any time, but pulling them off early in the season is preferred since cutting later after the wood hardens leaves basal buds to regrow. Summer pruning can be used on young trees to encourage leader development in such systems as the central leader, slender spindle and central axis (see Chapter 15). Normally it is best to remove several newly developing shoots just below the leader as soon as growth is 2–5 cm long. Summer pruning should not be used on trees with low vigour. The loss of leaf surface and the photosynthetic capability it represents can only aggravate the pre-existing vigour problem.

14.7 Root Pruning

As orchard intensification became a worldwide phenomenon in the latter half of the

20th century, many orchards were planted at a spacing unsuitable for the rootstock/scion/training system combination. As a result, overcrowding, decreased production and lower fruit quality occurred. A means was needed to control tree growth, and root pruning was one of the techniques evaluated. A review of root pruning (Geisler and Ferree, 1984b) reported that it was widely practised in European gardens to reduce tree size and promote flowering in the 1800s. In later years it was considered too dwarfing to be a recommended practice in either European or North American orchards.

14.7.1 Effects on physiological processes

Root pruning of non-bearing apple trees in the greenhouse temporarily reduces net photosynthesis, transpiration and leaf water potential (Geisler and Ferree, 1984b; Schupp and Ferree, 1990). When roots are removed by pruning, assimilates are redistributed to the root system, as evidenced by the increase in small roots in close proximity to the trunk, coupled with a reduction in leaf and new shoot growth. In a field study, root-pruned trees had more negative leaf water potential, reduced stomatal conductance and reduced transpiration (Schupp *et al.*, 1992). There was little effect on concentrations of leaf nutrient elements (Schupp and Ferree, 1987; Schupp *et al.*, 1992).

Shoot-tip ethylene production was reduced at 3, 9 and 17 days after root pruning, while the concentration of the ethylene precursor, 1-aminocyclopropane-1-carboxylic acid, in the xylem sap was unaffected. The concentration of cytokinin in the xylem sap was reduced 1, 3 and 9 days after root pruning (Schupp and Ferree, 1994). Thus, ethylene and cytokinin did not appear to be responsible for the reductions in growth caused by root pruning.

Although root pruning reduces photosynthesis and transpiration, it has no influence on the carbohydrate fractions in the leaves or shoots, but causes an increase in soluble and insoluble fractions in the roots (Ferree, 1989). The consistent water-stress effect found from root pruning probably explains most of the

growth response, as growth rate recovers along with regeneration of the root system and its ability to meet evapotranspirational demand. During the interim stress, the tree reduces water use by stomatal closure and minimizes transpirational surface through reduced shoot and leaf growth. The shift in plant hormones may also play a role directly by influencing growth or indirectly by influencing water relations.

14.7.2 Effects on growth

Results from greenhouse studies on young apple trees showed that root pruning decreased leaf number per tree, leaf size, total leaf area, shoot growth and decreased dry weight of leaves, shoots and roots (Geisler and Ferree, 1984a; Ferree, 1989; Schupp and Ferree, 1990). In the field, root pruning reduced trunk cross-sectional area, shoot length, shoot number to spur ratio, shoot leaf size, and shoot leaf area to spur-leaf area in cropping apple trees (Schupp and Ferree, 1987, 1988; Ferree, 1992).

The overall growth effects resulting from root pruning were sufficient to reduce pruning time and increase within-canopy light levels. Canopy light penetration and spur quality were increased. The more severe (the closer to the trunk) the root pruning, the greater were the effects on growth.

Compared with young greenhouse-grown trees, the effects of root pruning are much greater and of longer duration on bearing trees in the orchard. The presence of crop and its effect on root regeneration explain the stronger response. For example, the annual increase in trunk cross-sectional area of fruiting trees was reduced 44% by root pruning, but only 14% in deblossomed trees (Schupp *et al.*, 1992). The presence of crop reduced root regeneration and was, therefore, of primary importance for season-long reduction in vegetative control by root pruning. The resulting long-term water deficit is thought to be the means by which shoot growth is reduced. Lenz (1986) showed that cropping trees increased water usage compared with non-cropping trees. In a 6-year root-pruning study, shoot growth of 'Jonathan' apple was reduced approximately 30% each year (Fig. 14.7a), except the single year where rainfall each month of the growing season greatly exceeded the long-term average (Ferree, 1992).

Root pruning results in root regeneration in close proximity to the cuts. The timing of root pruning affects how much root regeneration takes place in a season. Considerable root regeneration was evident at the end of the growing season on trees root-pruned while dormant or at full bloom. Root regeneration was less on roots pruned at June drop and minimal in preharvest root-pruned

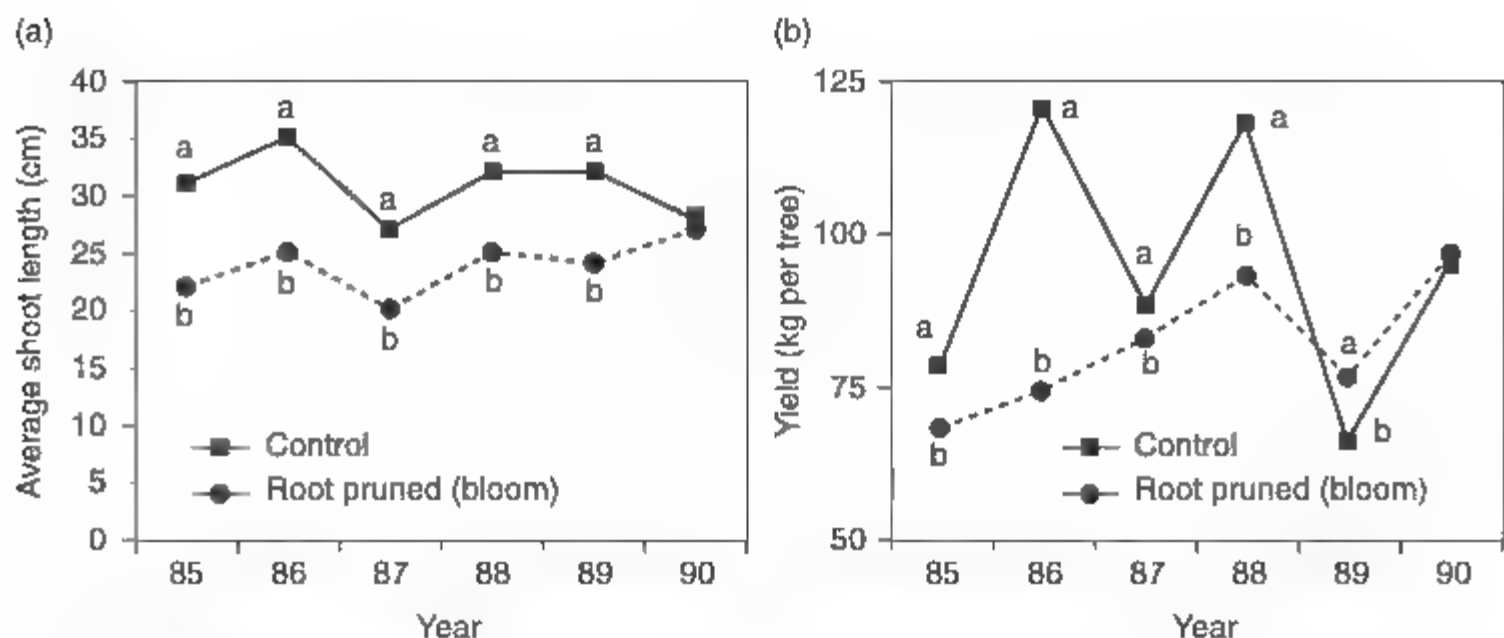


Fig. 14.7. Influence of root pruning over 6 years on shoot growth (a) and yield (b) of mature 'Jonathan' apple trees. Note the consistent growth effect and reduction in biennial bearing. (From Ferree, 1992)

trees (Schupp and Ferree, 1987). Excavations around trees root-pruned annually for 9 years showed a reduction in all root sizes. Roots < 1 mm in diameter were reduced 20% by root pruning, while the reduction in larger roots was nearly double this amount (Ferree, 1994a). The effect of root pruning on root distribution was greatest in the top 30 cm of soil, parallel to the location of the root-pruning cut at a depth of 25 cm. Roots below 30 cm were unaffected

14.7.3 Effects on fruiting

Compared with unpruned trees, root pruning increases yield efficiency (yield per trunk cross-sectional area), fruit colour and soluble-solids concentration. Preharvest fruit drop and fruit size are reduced. In large-fruited cultivars ('Melrose', 'Golden Delicious') the effect on fruit size was not enough to reduce yields, but in small-fruited cultivars, such as 'Jonathan', yield was reduced (Fig. 14.7b).

Root pruning at full bloom increased fruit soluble-solids concentration and slightly increased fruit firmness but decreased starch hydrolysis at harvest (Schupp *et al.*, 1992). Root pruning does not appear to affect blossom density or fruit set. In a long-term study over 9 years, root pruning reduced the biennial bearing pattern. Elfving *et al.* (1991) found that root pruning at full bloom in 'McIntosh' reduced the incidence of stem-cavity browning and brown core, but not in every year. Root pruning did not influence ethylene evolution at harvest, but did reduce post-storage ethylene. They concluded that root pruning at full bloom was generally less effective than daminozide in altering fruit behaviour

14.7.4 Practical implications

Generally, the closer to the trunk that root pruning is carried out, the more roots are cut and the greater the effect. For bearing trees, cuts 70–100 cm from the trunk on two sides are required to have the effects on growth and fruiting previously described (Plate 14.3). In a study comparing depths of 25 and

50 cm, there was no difference in response, as the upper 25 cm of soil has the greater concentration of roots. The optimum time of pruning appears to be around full bloom. In a study comparing responses of nine rootstocks or interstock combinations to the effects of root pruning, growth on all trees was reduced 20–30%, with no difference whether it was on dwarfing M.9 or vigorous seedling rootstock (Ferree and Knee, 1997). Multiple spray applications of low concentrations of cytokinins in the field were not successful in counteracting the reduction in fruit size due to root pruning.

Since root pruning has the potential to control tree size, a 10-year study evaluated the potential of root-pruning four cultivars grown in two orchard systems (Ferree and Rhodus, 1993). Root pruning was successful in containing tree size of apple trees planted at half the recommended in-row spacing. However, the reduced tree efficiency in the trellis system of dwarf trees or in the central-leader system of semi-dwarf trees resulted in minimal cumulative yield increase and no apparent economic advantage. It was concluded that it is better to plant systems at a spacing that avoids excessive crowding and allows an efficient balance of growth and fruiting without the need to intervene with practices such as root pruning.

Root pruning is a mechanical means of tree size and vigour control, which can assist in such situations as improper spacing for rootstock or cultivar or loss of crop to frost or following a particularly hard pruning to bring growth and fruiting balance to trees (Table 14.5). Under current market conditions there is a strong emphasis on producing large-sized fruit to satisfy the preferences of apple retailers. Since root pruning reduces fruit size, it must be viewed as a 'rescue treatment' for orchards with excessive growth and overcrowding, rather than a standard practice for reducing growth and pruning labour in orchards with more normal vigour.

It is important to understand the effects of root pruning since all trees purchased from a nursery have lost a portion of their root system. Several reports indicate no effect of removing most of the roots from nursery

Table 14.5. Summary of the influence of root pruning on the growth and fruiting of apple trees

Characteristic	Increased	Decreased	No change
Trunk growth		X	
Shoot length		X	
Shoot number		X	
Spur/shoot ratio	X		
Shoot-leaf size		X	
Spur quality	X		
Pruning time		X	
Canopy light penetration	X		
Biennial bearing		X	
Fruit set			X
Fruit yield (no. of fruit)			X
Fruit size		X	
Preharvest drop		X	
Fruit colour and quality	X		
Tree-yield efficiency	X		

trees after they are dug up on subsequent tree growth. However, trees propagated in the field and transplanted under ideal conditions caused a 32% reduction in growth compared with trees propagated in the field and not transplanted (Ferree, 1976a). Thus, the effect of root pruning can be significant and care should be taken not to sever roots through cultivation or other cultural practices if no reduction in growth is desired.

14.8 Training

Training utilizes various techniques, including pruning, to direct tree growth or form and the development of the structural framework of the tree. Although these forms can be very ornamental (Plate 14.4), generally the tree form fits some predesigned training system described in Chapter 15. Discussion in this chapter will be restricted to the techniques used to control tree growth in many orchards.

14.8.1 Bending

Physically bending a branch of an apple tree results in a reduction in terminal shoot growth and a redistribution of growth hormones, particularly auxin. The arrangement

of cells is changed and reaction wood is produced on the upper side of the branch. Reaction wood consists of xylem tissue on one side of the stem that has short, round tracheids and an altered pattern of wall thickening. Reaction wood can often be observed on the pruning cut of side limbs, with the upper half appearing denser than the lower half.

The stress created by bending has been shown to result in increased ethylene content in the internal air spaces within the branch (Robitaille and Leopold, 1974). The ethylene reaches a maximum 2 days after bending stress is imposed and returns to control levels in 3 weeks. A similar increase in ethylene was shown to occur by a paste application of auxin (naphthaleneacetic acid (NAA)) to the branch, which in turn caused an increase in ethylene. Thus, both auxin and ethylene may play a role in the responses induced by bending.

The growth reduction and increase in flower initiation caused by bending occur only during the season when the physical bending stress is imposed or the limb orientation is changed (Table 14.6). This effect has commercial value, since, by progressively changing branch orientation by inserting a longer spreader each year, a growth reduction can be achieved for several years. The progressive influence of spreading the stress

Table 14.6. Influence of bending on apple growth and flowering in the year of treatment (from Ferree, 1994b).

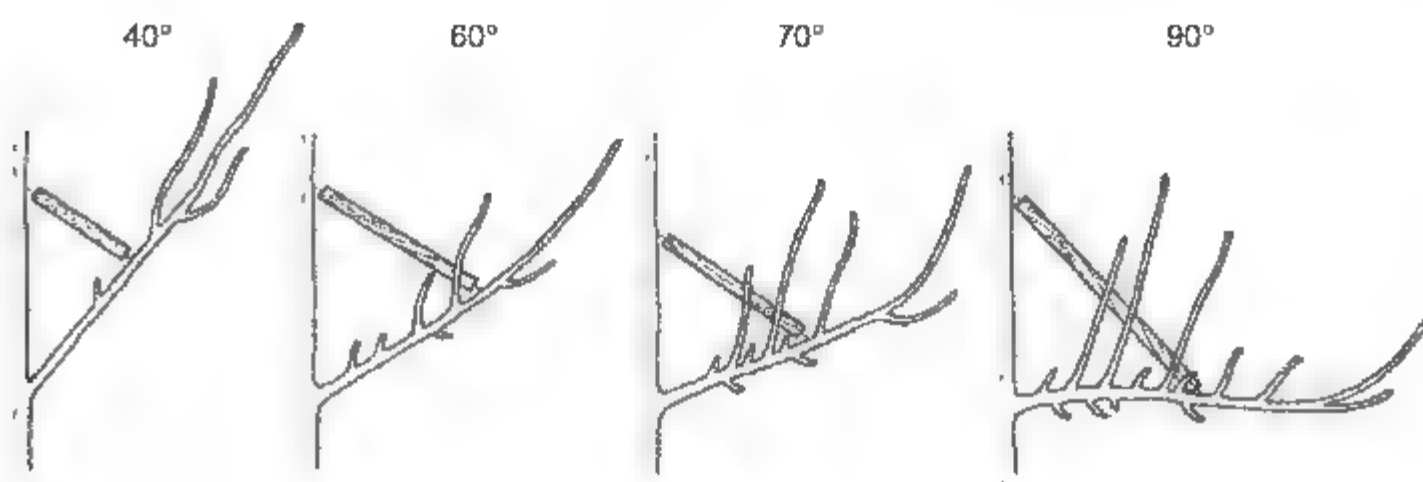
Treatment	Shoot length (cm)	Limb area (cm ²)	Flowers per limb area
Control	26.8a	2.14b	13.2b
Bending	24.4b	2.48a	15.3a

Values with letters uncommon are statistically different ($P = 0.05$)

over 2-3 years results in the greatest number of short, fruitful shoots and the fewest number of undesirable shoots. Cropping in successive years has a similar influence on the tree, but it is not as predictable as physically bending and does not occur until after the limb may have grown for several years and stiffened in an upright position, requiring considerable force or weight to change its orientation. The shoot-growth reduction that results from bending is associated with a similar reduction in root growth, so that the top-to-root ratio of the young tree is maintained.

Forshey *et al.* (1992) suggested that the reduced vegetative vigour in limbs that are bent reduces the production of gibberellins, which are antagonistic to flowering. The formation of moderately vigorous lateral shoots and spurs creates additional sites for flower formation. These two effects result in increased flowering and earlier fruiting. Fruit quality is also improved because of improved light penetration and because more fruit hang free instead of rubbing against the branch on more upright limbs.

The bending of a branch influences not only the amount of growth that occurs but also the location where shoots arise (Fig. 14.8). The influence of auxin begins just below the shoot tip and, as the orientation away from vertical increases, the auxin influence progresses down the branch and buds on the upper side are released from the hormonally induced apical dominance and begin to grow. Thus, the more the branch orientation is changed towards the horizontal, the greater the number of shoots released towards the branch base. If basal shoots are released due to bending too severely, they tend to be very vigorous and upright and often require removal during the dormant season. By bending and changing orientation only 10-15° in any year, shorter shoots are produced mostly on the outer half of the branch. If excessive spreading or a heavy crop load on the tip of the branch brings the branch to a horizontal or below-horizontal position, vegetative growth on the weeping tip portion nearly ceases and several very vigorous suckers will form from buds on the highest point of the bend. This undesirable

**Fig. 14.8.** Influence of various degrees of bending on distribution and amount of growth of an apple branch

type of response can be avoided by not bending the limb beyond about 60° from vertical and avoiding overcropping on the tips of scaffolds of young trees.

Several reports indicate that the inclination of the scion, particularly if horizontal, reduced growth and increased flowering (Tromp, 1972). The study concluded that the reduction of growth and promotion of flowering are independent phenomena and shoot orientation interferes in the later phases of flower formation. The effect on flowering was equivalent to that caused by daminozide. A field study over 5 years with 'Golden Delicious'/M.9 found that inclining the trunk at planting 45° or 60° from the vertical reduced the rate of shoot elongation by 40% and trunk circumference growth by 17% and 27%, respectively (Bargioni *et al.*, 1995). Root total dry weight was reduced by inclination and roots were more numerous and more elongated in the direction of inclination. The authors propose that the physiological basis of the phenomenon may reside in the asymmetric distribution of hormones caused by the inclination. These effects of inclination probably influence trees trained in such systems as the Lincoln canopy or Tatura trellis, where trunks or branches are inclined and secured to the trellis framework.

Practically, bending is accomplished using many techniques. In central-leader training, scaffold limbs are spread using wooden, metal or plastic spreaders, either notched or pointed to keep them in place. These are normally inserted before growth starts and can be removed after 4–6 weeks of growth. Others prefer to bend by tying limbs down to other limbs or anchors in the soil or fastening to the support system. The ties must be watched and cut if they begin to girdle the limb. Weights have also been used and again care must be given to avoid girdling. Spreaders and ties move a limb to a given position, but with weights it is more difficult to know exactly the degree of bending that will occur. Special rubber bands can be used to bend actively growing shoots or a leader, and again the degree of bending is difficult to ascertain.

Although bending has been commonly used to reduce shoot extension and promote flowering, consistent effects were not

always found. In training systems such as the slender spindle or hybrid tree cone orchard system (HYTEC), bending is used to weaken the leader and encourage growth and fruiting in the lower scaffolds. In a study that compared the influence of bending the leader first one way and then the opposite way for different lengths of time, the length of time the leader was bent had no effect on shoot growth, but 15 days appeared to increase flowering, with no benefit from longer times in the bent position (Ferree and Schmid, 1999). The hypothesis that the response to bending may differ at various times during spring when growth is initiated was refuted in this study, as no effect was found (Fig. 14.9). Bending in combination with minimal pruning was successful in reducing growth and increasing production of young 'Fuji' trees (Ferree and Schmid, 1994). In a study with two cultivars that compared responses on the dwarfing rootstock Mark and the semi-dwarf rootstock M.7a, bending scaffolds increased flowering in the 2 subsequent years and increased cumulative yield 11% on Mark, but had no effect on the yield of trees on M.7 (Ferree, 1994b). It is unclear why bending provides an economic benefit by reducing or redirecting growth in some instances and in others the effects are negligible.

14.8.2 Phloem interruption

Scoring and ringing, which cause the interruption of the downward flow of carbohydrates and hormones in the phloem, have been shown to alter growth and fruiting in apple. The degree or length of time that translocation through the phloem is interrupted is influenced by whether and how much of the bark and phloem are removed. Scoring, which is a circumscribing cut through the bark, but not into the wood, has the smallest effect. Ringing, which removes different amounts of bark in a circumscribing ring, increases in severity with the amount of bark that is removed until the ultimate of tree death occurs when the tree is unable to form new tissue to bridge the ring.

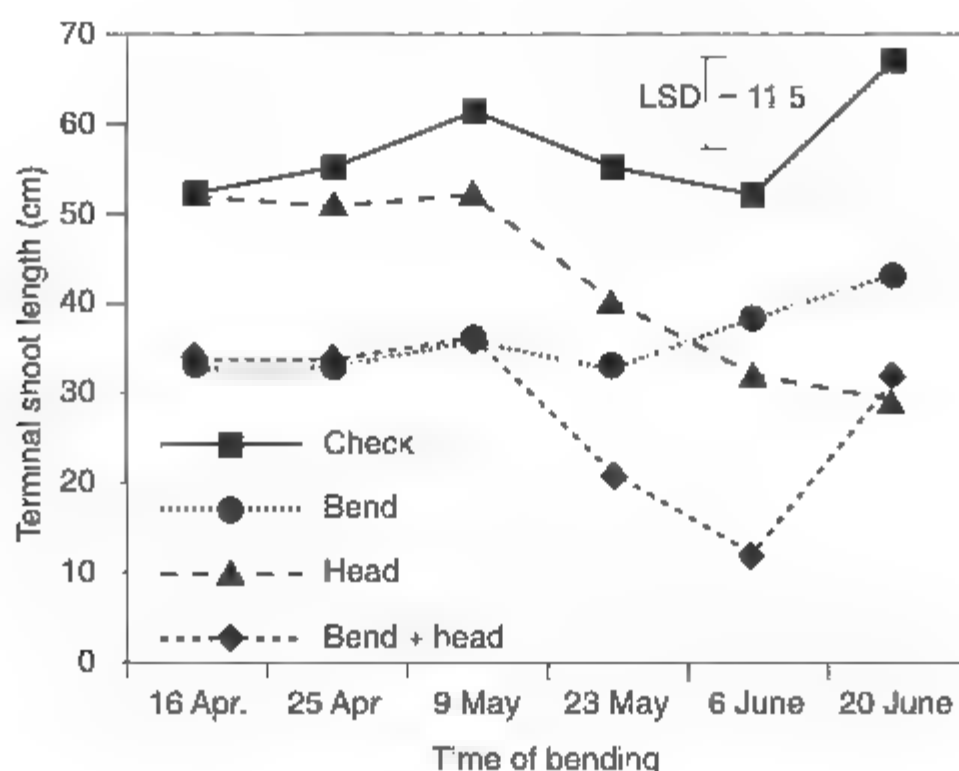


Fig. 14.9. Interaction between time of bending and heading vigorous laterals on the central leader of 'Regal Gala' on M.7 rootstock (from Ferree and Schmid, 1999)

Scoring and/or ringing interrupt phloem translocation, which causes a build-up of the products of photosynthesis in the portion of the tree above the cut. Growth hormones produced in the apical meristem and young leaves are also translocated in the phloem and thus also play a role in the effects produced. The photosynthetic and transpiration rates of leaves above the scoring cut are reduced for up to 2 weeks, but recover to the control levels of unscored plants in 4 weeks. This effect is thought to be due to the carbohydrate feedback mechanism, which causes photosynthesis to slow or stop when carbohydrates build up and are not translocated out of the leaves. If a ring of bark is removed, the effects on photosynthesis last for more than 4 weeks and a greater reduction in growth would be expected. A number of studies show that phloem interruption reduced terminal growth, trunk cross-sectional area, shoot diameter and number of shoots (Greene and Lord, 1983; Autio and Greene, 1992).

Trunk scoring 19 days after full bloom reduced fruit size in 'Cortland' and 'Delicious' apples, reduced firmness in 'Delicious' and increased soluble solids in both cultivars (Greene and Lord, 1978). After storage, 'Cortland' apples from scored trees had a higher incidence of bitter pit and cork, while 'Delicious' fruit exhibited more breakdown.

Elfving *et al.* (1991) found that trunk scoring or ringing increased soluble solids and retarded loss of flesh firmness before harvest and following storage, but had little effect on starch hydrolysis. Scoring or ringing decreased the incidence of brown core, stem-cavity browning and scald in some years. Scoring also reduced post-storage ethylene evolution. 'McIntosh' fruit were longer and had larger pedicel diameters and weights and more colour from trees that were ringed (Webster and Crowe, 1969). Results from these studies were variable on the effects of phloem interruption on fruit size and quality and were often not consistent from year to year.

More severe versions of phloem interruption (Plate 14.5) can be done with a chainsaw (Hoying and Robinson, 1992). Chainsaw ring girdling involves making two overlapping horizontal rings, 2 cm deep and spaced 20 cm apart on the trunk. With guillotine girdling, two chainsaw cuts were made to remove all the tissue on opposite sides of the trunk to a depth of one-third the radius of the trunk. Both techniques reduced growth, although not as much as root pruning, with the advantage that fruit size was not reduced by girdling (Hoying and Robinson, 1992). Caution must be exercised when applying herbicides under trees that have undergone these treatments to avoid damaging the callus tissue that forms as

the girdles heal. Furthermore, this treatment has induced the development of heart-rot in some trees. It is cautioned that this technique should be used only to extend the economic life of orchards that are nearing the end of their useful lifespan (Hoying, 1993)

14.8.3 Notching

Notching is a phloem-interruption technique used to stimulate lateral branching from buds that would not normally grow. The technique removes a 2–3 mm wide strip of bark directly above a bud. The cut extends down to the secondary xylem and around about one-third of the circumference of the stem. Notching stimulates lateral branching by interrupting the downward movement of auxin from the shoot tip (Tamas, 1987). As long as the phloem remains severed and auxin is prevented from reaching the lateral bud, the growth and development of the bud will be induced. Greene and Autio (1994) found that the most efficient time to notch was approximately 2–4 weeks before full bloom. Buds notched shortly after bloom grew less than those notched earlier. Although notching increased the growth of all bud sizes, the largest buds were more likely to develop into a lateral shoot and the shoot would be longer than from small buds. Notching was most effective at inducing shoot growth from buds on the top of the branch, less effective for buds on the side and least effective for buds on the underside of the branch. The percentage of buds that developed into shoots was not influenced by wood age or location along the length of the shoot. Notching was able to overcome bud inhibition imposed by a shoot apex by preventing the movement of auxin to

the bud, but it was not able to overcome inhibition due to geotropism. Shoots that develop from notched buds usually have a sharper crotch angle than shoots that develop from buds that were not notched (Verner, 1955). Crotch angle can be improved by using clothes-pegs or other techniques, as previously described. Greene and Autio (1994) found notching consistently effective, indicating that one could reasonably expect more than 80% of the notched buds to grow into lateral shoots. Notching is a very useful technique for inducing shoots for scaffolds and for balancing growth in young trees. In addition to using pruning, bending and notching to induce shoot growth, chemical growth regulators (Chapter 17) and the removal of the youngest cupped leaves on the apical meristem (Chapter 6) can be used in appropriate situations. Enclosing the base of very vigorous upright leaders in plastic sleeves just prior to the beginning of growth has been used to stimulate buds to grow (Plate 14.6).

14.9 Conclusion

Pruning and training occupy a unique position in the management of an orchard, being the most costly cultural practices and the practices most often poorly done, with dramatic influences on orchard efficiency and fruit quality. Pruning interacts with other cultural practices, such as fertilization, fruit thinning, growth regulators and pest control. Fruit quality is a sensitive indicator of the effectiveness of pruning, as canopy light distribution influences all aspects of yield and fruit quality. Although good pruning does not guarantee success, economic success without good pruning is inconceivable.

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15 Apple-orchard Planting Systems

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15.1 Introduction

Orchard planting systems are specific combinations of orchard layout and management that are designed to improve orchard production efficiency. They include the management variables of rootstock, tree spacing, tree arrangement, canopy shape, tree-training method, pruning method and tree support system. Over the last 30–40 years, numerous planting systems for modern apple orchards have been developed, each with their own merits. Although the systems differ in specific management practices, many of the modern planting systems have similarities and are based on the same underlying principles. They all have the goals of high early yields, high sustained yields and excellent fruit quality. Growers can achieve these goals with any of several orchard planting systems. There may be no perfect planting system for all growers, but how a fruit grower integrates the practical management variables of each system determines his/her opportunity for economic success with the new orchard. Barritt (1992) has likened each of the management variables that make up an orchard planting system to puzzle pieces. Fruit growers must successfully integrate these puzzle pieces to be profitable. Ignoring one or more of the puzzle pieces has resulted in

considerable variability in grower success with each planting system (Hoying and Robinson, 2000).

Modern orchard planting systems are based on higher tree densities than were common 50 years ago when most orchards were planted at a density of 70–100 trees ha^{-1} . Today tree densities of modern apple orchards range from 1000 to 6000 trees ha^{-1} , with some systems using densities up to 10,000 trees ha^{-1} . This increase in tree density has been made possible by the development of dwarfing apple rootstocks. The combination of dwarfing rootstocks and higher tree-planting densities has dramatically improved cumulative fruit production over the first 10 years of an orchard's life. With most modern high-density planting systems, a small but significant yield is expected during the second growing season of the orchard. Substantial yields are expected in the third year and mature yields are expected by year 5 or 6. In contrast, traditional low-density systems on vigorous rootstocks began production around year 6 or 7 and did not reach mature yields until year 15.

Orchard planting systems can be categorized by tree canopy shape. There are four basic shapes of canopies: spherical canopy shapes, conic canopy shapes, flat-fan canopy shapes and Y or V canopy shapes.

European gardeners have utilized various clonal dwarfing and semi-dwarfing rootstocks for centuries and have trained apple canopies into many geometric shapes (Huggard, 1980). The most common of these were the espaliers grown along walls and fences. However, most commercial apple orchards in the 1800s and early 1900s utilized trees on seedling rootstocks and had large globular-shaped tree canopies. Other tree shapes were not an integral part of commercial orchard planting systems until the middle of the 20th century. In the second half of the 20th century, researchers and growers began to search for more efficient shapes and systems. There have been nine international symposia in the last 40 years convened by the International Society for Horticultural Science's working group on Orchard and Plantation Systems that have chronicled the developments in high-density orchard systems over the last 50 years. This collection of papers, published in *Acta Horticulturae* volumes 65, 114, 160, 243, 322, 349, 451, 513 and 557, is suggested as further reading.

15.2 Spherical-shaped Canopy Systems

The most common tree form in traditional apple orchards in Europe and North America in the late 1800s and early 1900s was a large globe-shaped tree with a height of 6–8 m and a main trunk length of 1.8–2 m, which provided enough room under the canopy for cattle to graze (Walker, 1980). The tree was planted on a seedling rootstock, using a low tree density that required large spreading trees to fill the space allocated to each tree. This required multiple large scaffold branches or leaders per tree, which formed large globe-shaped canopies at maturity and required 10–15 years to produce high yields (Plate 15.1). In the 1920s, Sir Ronald Hatton of East Malling Research Station collected, categorized and then released the Malling series of clonal dwarfing rootstocks from all over Europe, which spurred the commercial development of orchard systems based on smaller trees (Walker, 1980).

15.2.1 The bush-tree system

In the 1930s, as research results from clonal dwarfing rootstock trials were obtained, a smaller version of the large globe-shaped tree on clonal rootstocks, named the bush tree, was developed in Holland and England (Wertheim, 1981). The tree canopy was lowered to only 50 cm above the ground, which no longer allowed animal grazing in apple orchards. The tree height was reduced from 6–8 m to 4–5 m and tree density was increased from 70–100 trees ha^{-1} to 250–350 trees ha^{-1} . This tree system had earlier production, due to the use of semi-dwarfing rootstocks, easier management, due to the smaller trees, and higher orchard productivity.

15.2.2 Spindle-bush system

In the late 1930s the spindle-bush system was developed in Germany by Schmitz-Hubsch and Heinrichs (1942), which revolutionized apple growing (Wertheim, 1981). The spindle-bush was based on the fully dwarfing M.9 rootstock and utilized, for that time, high tree densities of 1000–1500 trees ha^{-1} . The trees were spaced 2.5 m in the row and had a tree height of only 2 m. The tree had a single leader and was supported by a pole. The horizontal fruiting branches originated from the leader. The use of M.9 and high tree densities gave very high early production, easy management and good fruit quality. The use of the spindle-bush system was short-lived, but it led directly to the slender-spindle system in the 1960s, which has become one of the leading systems in the world.

15.2.3 Advantages and disadvantages of spherical-shaped systems

The primary advantage of spherical shapes is that they are generally the natural shape produced by apple trees. However, the canopies generally have a large shaded centre core that is unproductive and produces poor fruit quality. In addition the traditional spherical canopies, although large at matu-

rity, required too much time to develop. Globe-shaped canopy systems were the dominant tree form through the first half of the 20th century but were replaced by conic, planar and V systems in the later half of the century. None of the current leading orchard systems is based upon a spherical canopy shape.

15.3 Conic-shaped Canopy Systems

In the early 1960s, researchers (Heinicke, 1963, 1964; Looney, 1968; Cain, 1970, 1972) studied the light distribution within the canopies of large globe-shaped apple canopies and concluded that much of the canopy received too little light for good fruit quality and was unproductive. They proposed a conic or pyramidal canopy shape as an improved tree form. This tree form was then developed into several planting systems.

15.3.1 Central-leader system

The central-leader system was developed by Heinicke (1975) in North America and McKenzie (1972) in New Zealand. This tree-training system has been widely adopted in North America, New Zealand, Australia and South Africa. The system has a pyramid-shaped tree with tiers of branches spaced along the trunk. It is a medium-density system with tree densities ranging from 300 to 700 trees ha⁻¹. Typically trees have three to four tiers of branches spaced along the trunk and a tree height of 4–5 m (Fig. 15.1 and Plate 15.2). The trees are usually not supported with a trellis or individual tree stakes. Semi-vigorous rootstocks, such as M7, MM.106, MM.111 and M793, are used. The widest part of the tree is at the bottom tier. The bottom tier of branches is 60–90 cm above the ground and has four or five branches. The second tier of branches is commonly 60 cm to 1 m above the first tier and has four branches. The third and fourth tiers are spaced about 60–80 cm apart and typically have three branches. Years of experience have led growers to increase the

distance between the bottom and second tier to a minimum of 1 m and to leave gaps in the canopy to increase the light penetration to the bottom tier.

The canopy is developed by heading the leader annually to develop tiers of branches just below the heading cut (Table 15.1). Branches in each tier are manually spread to an angle of 30° above horizontal for the bottom tier and to horizontal for the upper tiers. Upper-tier branches are shortened when they become too long to maintain the conic shape. The New Zealand version of the central-leader tree maintains gaps between branches in each tier for ladder bays and light penetration to the centre of the tree.

15.3.2 Mini-central-leader system

The mini-central leader was developed by R. Norton in New York State in the late 1970s. It is similar to the central leader, but utilizes semi-dwarfing rootstocks and slightly higher tree densities, ranging from 500 to 1000 trees ha⁻¹. Trees are typically supported with an individual 2.5 m tree stake. Trees are pyramid-shaped, with two tiers of permanent branches along the trunk and a tree height of 3–4 m. Semi-dwarfing rootstocks, such as M.26, M.9/MM.111 or M.9/MM.106 interstems, G.30 and Supporter 4, are used

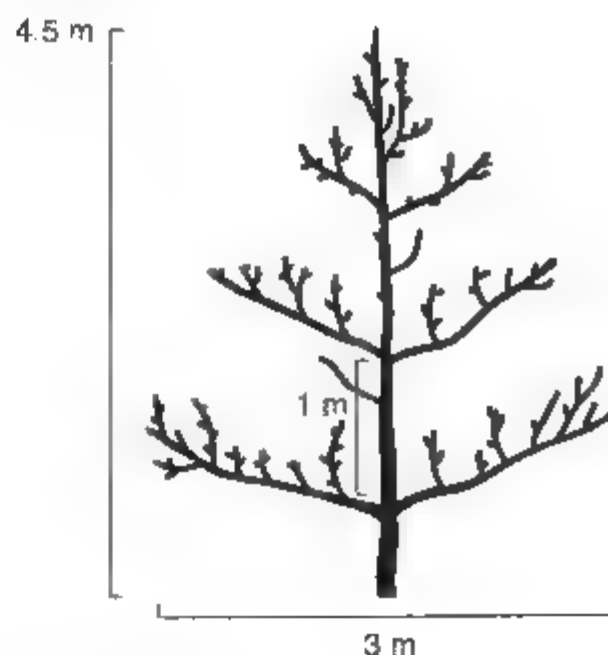


Fig. 15.1. The central-leader tree has a free-standing dominant trunk, a conic shape and distinct tiers of branches, with a 1 m gap between tiers.

Table 15.1. Simplified pruning and training plan for the central-leader system (NB Northern-hemisphere dates.) (Adapted from Robinson and Hoyal, 1994.)

First year	
At planting	Adjust graft union to 10 cm above soil level. Remove all scaffolds below 60 cm, using a flush cut. Trees with three or more scaffolds (25 cm long) should be headed at 110 cm above the soil line, with all scaffolds headed by removing one-third their length. Trees with fewer than three feathers should be headed at 90 cm and all feathers removed, using a bevel cut, leaving a 2 cm stub.
1–2 cm growth	Rub off second and third buds below the new leader bud to eliminate competitors to the leader shoot. Deflower tree.
5–10 cm growth	Attach clothes-pegs to new side-shoots on leader to promote wide crotch angles.
Early summer	Install tree support system that will allow tree to be supported to 3 m. Attach tree to support system with a permanent tree tie above first tier of scaffolds, leaving a 5 cm diameter loop to allow for trunk growth.
July	Tie developing leader to support pole with permanent tie. Remove clothes-pegs.
Second year	
Dormant	Head leader, removing one-third to two-thirds of last year's growth, depending on tree vigour. The more vigorous the leader and scaffolds, the less severe the heading cut should be. Remove any side-branches remaining that compete with the leader. Scaffold branches should be headed, removing one-third of last year's growth.
5–10 cm growth	Attach clothes-pegs to lateral shoots developing on 1-year-old wood to ensure good crotch angles. Select leader and pinch out or remove competing shoots.
Mid-July	Spread bottom-tier branches to 45° using 30 cm nail-tipped limb spreaders. Spreading should be done early in the growing season for vigorously growing trees, later for weaker-growing trees. Remove clothes-pegs.
Third year	
Dormant	Head leader 1 m above the top branch of the bottom tier of branches to promote permanent second-tier scaffolds. Remove vigorous branches between first and second tiers of branches.
5–10 cm growth	Attach clothes-pegs to lateral shoots developing on 1-year-old wood to ensure good crotch angles. These will form permanent second tier. Select leaders and pinch out or remove competing shoots.
August	Remove clothes-pegs.
Fourth year	
Dormant	Head the leader, removing one-third to one-half of last year's growth. Remove excessively vigorous non-scaffold limbs, particularly those competing with the leader. Reposition 30 cm spreaders where needed within the tree.
July	If bottom-scaffold branch length is approaching one-half in-row spacing, respread with 1 m nail-tipped spreaders to 80° from vertical.
August	Lightly summer-prune to encourage light penetration and maintain pyramidal tree shape.
Fifth year	
Dormant	Head leader, removing one-third of last year's growth. Remove shoots that are competing with the leader. Lightly dormant-prune to invigorate weak areas, thin out overcrowded areas and remove hanging branches. Respread rest of bottom tier of branches with 1 m spreaders.
Late May	Chemically thin then follow up with hand thinning to appropriate levels to ensure regular annual cropping and adequate fruit size.
July	Spread second-tier branches with 30 cm nail-tipped spreaders where necessary.
August	Lightly summer-prune to encourage light penetration and maintain pyramidal tree shape.

Continued

Table 15.1. *Continued.*

Sixth year	
Dormant	Head leader 1 m above established second tier to establish third-tier scaffolds 1 m above second tier. Lightly dormant-prune to invigorate weak areas, thin out overcrowded areas and remove hanging branches. Reposition bottom-tier spreaders where necessary
August	Lightly summer-prune to encourage light penetration and maintain pyramidal tree shape
Seventh year	
Dormant	DO NOT HEAD LEADER. Remove all shoots competing with the leader, defining permanent third-tier scaffolds. Remove largest one or two branches between first- and second-tier scaffold limbs
August	Lightly summer-prune to encourage light penetration and maintain pyramidal tree shape
Mature-tree pruning	
Dormant	Limit tree height by cutting back into 2–3-year-old wood. Remove large branches between tiers of scaffolds. Remove least desirable bottom-tier scaffold so that no more than four limbs remain. Prune back lower-tier scaffolds to a side-branch to facilitate movement of equipment and preserve fruit quality. Second- and third-tier branches can be removed if excessively vigorous. During dormant-pruning of the 12th to 15th year, remove second-tier east- and west-growing branches to create a palmette or flat fan-type top
August	Summer-prune off vigorous upright shoots to increase light penetration and maintain fruit colour. Occasionally tuck upright shoots where additional fruiting wood is needed

As with the central-leader system, the canopy is developed by heading the leader annually until the first two tiers are developed and by manually spreading the branches in each tier to an angle of 30° above horizontal for the bottom tier and to horizontal for the second tier. Above the second tier of branches no permanent branches are allowed to develop, but small fruiting branches on the leader are retained and allowed to crop and bend below horizontal. The bottom tier of branches is developed at 60–90 cm above the ground but has only four branches. The second tier of branches is about 1 m above the first tier and also has four branches. After the second tier of branches is developed, the leader is left unheaded and allowed to fruit. After the leader reaches the desired mature tree height, the leader is cut annually to a side-branch at about 3–3.5 m. Second-tier branches are shortened when they become too long to maintain the conic shape.

15.3.3 Palmette-leader system

The palmette-leader (PL) system is a modification of the central-leader system that was developed by Lakso *et al.* (1989a), which is designed as a conversion form for mature central-leader trees. In many cases as central-leader trees age, the upper limbs outgrow the lower tier, resulting in excessive shade in the bottom of the trees. There is a strong tendency for the upper scaffold limbs to grow more vigorously than the lower limbs, due to better light exposure. The shading that develops reduces flowering and fruiting in the centre of the tree.

The PL shape was designed to improve the light distribution in the tree canopy. This tree is developed by removing upper east- and west-growing branches of a mature central-leader or mini-central-leader tree, resulting in a flat north-south-orientated palmette (i.e. fan-shaped) top. The lower tier or tiers of limbs are left intact. The primary advantage of the PL form is that large gaps are created

in the upper east and west sides of the canopy, which guarantee good light exposure to all parts of the tree. A more subtle benefit is that good light penetration into the tree centre is found throughout the season. A useful feature of the palmette top leader is that it can be adapted to east-west-orientated rows. With east-west-planted rows, the flat fan-shaped top of the PL trees may still be orientated north-south (i.e. perpendicular to the row direction). This creates a gap between trees in the row for light penetration to the lower limbs of the canopy.

This tree form is most useful as a conversion form for semi-dwarf to semi-vigorous central-leader trees between the ages of 7 and 15 years old. The conversion process is done over a 3-year period by removing two or three upper limbs each year. When trees are between 7 and 15 years of age, the upper-tier limbs are not large enough for the removal of two or three upper-tier east- or west-growing branches per year to result in excessive pruning and reduced yield. With more severe pruning, yield is reduced excessively. The PL system results in improved light distribution to the bottom of the tree and thus improved fruit quality. With older trees, very large limbs must be removed to make the conversion to PL and care should be taken to make the conversion slowly over several years so that excessive vigour and a reduction in yield are not induced. Pruning of this tree form is simplified compared with that of the central-leader tree. Pruning consists of keeping the palmette top narrow, thinning out excess limbs in the top and removing upright growth from the bottom tier of scaffolds.

15.3.4 Slender-spindle system

The slender-spindle tree was developed by Wertheim (1968) in the early 1960s and was designed to improve early yields and management efficiency by planting higher tree densities and reducing tree height to allow all management to be done from the ground. This system has become the dominant planting system in many parts of Europe (Oberhofer, 1987; Wertheim *et al.*, 2001).

The tree is a narrow, fully dwarf, conic-shaped tree (Fig. 15.2), which allows planting of very high tree densities, ranging from 1500 to 4000 trees ha^{-1} in either single-, double-, triple- or multiple-row beds. The most common rootstock used is M.9, but other stocks of the same dwarfing level, such as B.9 and G.16, are also used. The trees are always supported with either an individual tree stake or a single- to three-wire trellis. The width of the canopy is typically less than 2 m and tree height ranges from 2 to 3 m. In Germany, mature tree height of slender-spindle trees was related to row spacing by dividing row spacing by 2 and adding 1 m (Winter, 1981).

The slender-spindle tree typically has a single permanent tier of branches, which are developed by heading an unbranched tree (whip) at planting or by planting a branched tree (feathered) from the nursery (Table 15.2). After planting, the central leader is cut at 30 cm above the highest side-shoot. The feathers or lateral branches, which develop during the first year, form a permanent tier of branches. They are tied horizontal during the first or second year to induce cropping.

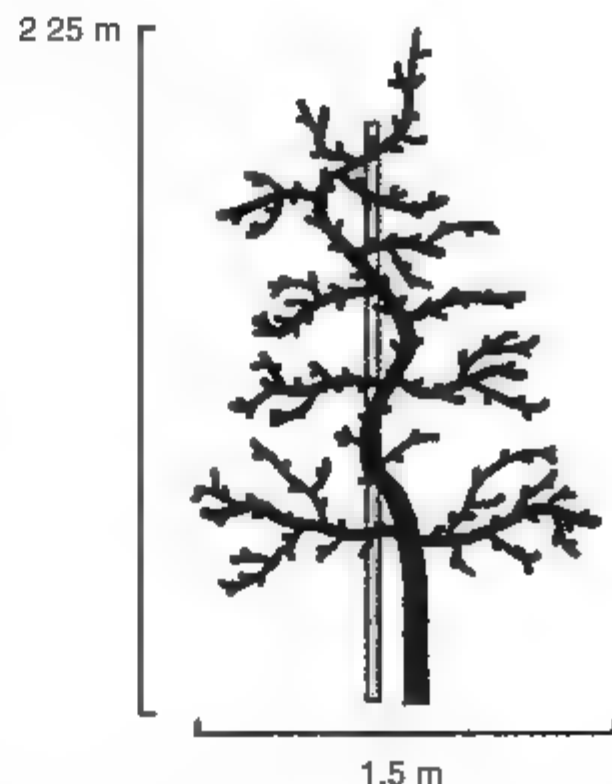


Fig. 15.2. The slender-spindle tree has a supported zigzagged trunk to limit tree height, a conic shape and a permanent basal tier of branches. Lower branches are shortened to keep the tree slender while upper branches are shortened or removed and replaced to maintain the conic shape.

Table 15.2. Simplified pruning and training plan for the slender-spindle system. (NB Northern-hemisphere dates.) (Adapted from Robinson and Hoying, 1994.)

First year	
At planting	Plant highly feathered trees. Adjust graft union to 10 cm above soil level. Remove all scaffolds below 60 cm, using a flush cut. Trees with three or more scaffolds (25 cm long) should be headed at uppermost scaffold. The uppermost side-branch should then be tied up as the new leader. Scaffolds longer than 45 cm should be headed by removing one-third their length.
5–10 cm growth	Attach clothes-pegs to new side-shoots on leader to promote wide crotch angles.
Early summer	Install tree-support system that will allow tree to be supported to 2.5 m. Attach tree to support system with a permanent tree tie above first tier of scaffolds, leaving a 5 cm diameter loop to allow for trunk growth.
July	Tie developing leader to support pole with permanent tie. Remove clothes-pegs.
Second year	
Dormant	Where growth has been good (> 45 cm of terminal growth), tie leader and vigorous scaffold branches horizontal. Alternatively, remove leader down to a horizontal scaffold branch and tie it up as the new leader.
Mid-June	Tie leader back to stake, allowing smoothly curving bends to remain. Hand-thin fruits to 15 cm apart.
August	Tie up lower scaffolds not expected to support the crop.
Third year	
Dormant	Where previous leader bending has significantly weakened the top of the tree, DO NOT PRUNE. Where leader is vigorous, tie leader horizontal or alternatively remove leader down to a suitable horizontal side-branch and tie it up as the new leader.
Mid-June	Tie leader back to stake, allowing smoothly curving bends to remain. Tie down vigorous limbs that will not bend with the weight of the crop. Hand-thin fruits to 15 cm apart.
August	Tie up lower scaffolds not expected to support the crop. Alternatively, do not tie up but prune back scaffolds to prevent limb breakage and preserve tree structure.
Fourth year	
Dormant	DO NOT PRUNE LEADER. Remove overly vigorous upright limbs that are more than two-thirds the diameter of the leader, using a bevel cut. Tie down other vigorous, upright limbs below the horizontal overlooked during third summer.
Mid-June	Tie leader to stake, allowing smoothly curving bends to remain. Tie up fruitful scaffolds that will not support crop weight.
August	Lightly summer-prune to encourage light penetration and maintain pyramidal tree shape. Tie up lower scaffolds not expected to support the crop.
Fifth and sixth year	
Dormant	Limit tree height by cutting leader into 2- or 3-year-old wood back to a horizontal fruiting branch. In each year, remove at least one undesirable bottom-tier scaffold until four remain. Shorten bottom-tier scaffolds by pruning back to side-branch to facilitate equipment movement and preserve fruit quality on lower limbs. Shorten branches that have become pendant back to horizontal portion of the branch.
August	Lightly summer-prune to encourage light penetration and maintain pyramidal tree shape.
Mature-tree pruning	
Dormant	Limit height by cutting leader back to a fruitful side-branch. Shorten bottom-tier scaffolds by pruning back to side-branch to facilitate equipment movement and preserve fruit quality on lower limbs. Shorten branches that have become pendant back to horizontal portion of the branch. Remove one or two vigorous upper-scaffold limbs each year, preserving all weak-fruiting wood and permanent lower-tier scaffolds.
August	Summer-prune to encourage light penetration and maintain pyramidal tree shape.

and to limit the width of the canopy. The leader is trained in a zigzagged manner up the support pole, either by annually removing the leader down to the first side-branch and tying up the lateral branch as the new leader or by bending the leader to 45° from the vertical each year and then annually tying it back and forth across the pole (Plate 15.3). These procedures limit the growth of the leader, which allows tree height to be limited to 2.5–3 m. The upper part of the tree is composed of small fruitful branches, which bend with crop below the horizontal.

In the 1970s, most slender-spindle orchards had densities from 1500 to 2500 trees ha⁻¹ and had a tree height and diameter (i.e. spread) of about 2 m. During the 1980s, higher tree densities of between 2500 and 3500 trees ha⁻¹ were common and a narrower and taller tree form was developed, with a tree diameter of 1.25–1.5 m and a tree height of 2.5 m. In the 1980s greater emphasis was placed on obtaining significant yield in the second year after planting by using feathered trees, where the feathers started at 50 cm above the soil. The low height of the feathers required significant labour to tie them up when they began to fruit to prevent fruit from touching the ground. In the late 1990s, the minimum height of feathers was raised to 80–90 cm (Balkhoven-Baart *et al.*, 2000). This eliminated the need for tying up branches. In addition, many growers have allowed tree height to increase to 2.75–3 m (Mantinger, 2000). In the 1990s, many slender-spindle growers began to avoid pruning trees after planting or during the first few years. If the central leader was cut to the highest side-shoot each year, a vigorous frame developed, which needed a lot of summer-pruning labour to maintain good light distribution in the tree for good fruit quality. Without pruning of the leader and with feathers starting at 80 cm, the tree can be allowed to crop in the second year, which gives natural bending of lateral branches to keep the canopy narrow (Mantinger, 2000).

The narrow, slender shape of the slender-spindle canopy helps ensure that most of the canopy is well exposed. However, in some cases, if the branches are too close together within the canopy with only small gaps between them, a high density of foliage

develops and shading results (Robinson *et al.*, 1989). This is especially a problem with vigorous growth, where these gaps can be closed very quickly in the season, leading to poor fruit colour and quality if the trees are not summer-pruned (Sansavini *et al.*, 1981, Corelli and Sansavini, 1989). The slender-spindle system has been most successful in more northern climates where natural tree vigour is less. In more southern climates, natural tree vigour on M.9 is often excessive, which makes it difficult to manage trees at the very high tree densities of slender-spindle.

15.3.5 North Holland spindle

The North Holland slender-spindle system was developed by a Dutch fruit grower, D. Huisman, in the Northern province of the country in the late 1970s (Wertheim, 1981). It is a modification of the slender-spindle system that is more slender (1–1.5 m diameter) and utilizes narrower in-row and between-row spacings. Typically the North Holland spindle is planted in a three-row bed. This results in higher tree densities than the traditional slender-spindle orchards. The trees are planted on M.9 and are limited to a 2 m height. The tree is developed in much the same way as a slender-spindle tree, but the lateral fruiting branches are cut back rather drastically to keep the tree slender and small. The North Holland spindle also differs from the slender-spindle in having a reduced amount of renewal pruning of lateral fruiting branches. This tree at maturity has a lower tier of three short, horizontal, permanent scaffold branches at a height of 70–80 cm on the leader. Above the lower tier there are numerous shortened, semi-permanent fruiting branches along a zigzagged leader. The greater severity of pruning used with the North Holland spindle compared with the slender spindle was intended to improve fruit quality by improving light exposure to the lower and centre portions of the canopy. The system has worked very well in low-vigour soils or climates. With more vigorous soils or climates, the severe pruning has stimulated too much growth, which has resulted in poorer fruit quality than other systems.

15.3.6 Slender-spindle multi-row or bed system

The slender-spindle multi-row or bed system was developed in Holland in the 1970s. It is a modification of the single-row slender-spindle system that eliminates the tractor alleys, leaving only a walking path between the rows. This results in very high tree densities. The beds can be from three to seven rows wide, with a tractor alley between beds (Wertheim, 1978b, 1981; Oberhofer, 1987). In a few experimental cases, tractor alleyways were eliminated completely and a full field system was planted and managed with over-the-row equipment (Wertheim, 1981). The trees are planted on M.9, or in some cases, the super dwarfing M.27 rootstock. Spacing between trees and between rows is similar (1.0–1.75 m). Mature tree height is 2 m and the tree canopy resembles that of a slender-spindle tree. The trees are supported by individual tree stakes. With most slender-spindle bed systems, the between-row spacing in the beds is less than the in-row spacing and trees are planted on a diagonal pattern, so that mini-rows are created diagonally across the beds. The diagonal alleyways across the beds aid in spray penetration to the interior of the beds, as well as providing picker access. The multi-row bed systems achieved very high production and light interception by the second or third season in the orchard (Palmer *et al.*, 1992). As the trees matured, shading between trees often resulted in reduced fruit quality and increased summer-pruning costs (Balkhoven-Baart *et al.*, 2000).

15.3.7 Vertical-axis system

The vertical-axis system was developed in the late 1970s by Lespinasse (1980) in southern France. Lespinasse (1977) categorized apple cultivars into four types, based on fruiting and growth habit. The vertical-axis system was designed to utilize the natural fruiting and growth habit of each cultivar. The vertical-axis system utilizes tree densities from 1000 to 2500 trees ha⁻¹, spaced at 1.0–2.0 m in the row and 4.0–5.0 m between the rows. The most commonly used stocks are M.9 and

M.26. Trees are supported with a single- to multiple-wire trellis up to 3 m high. The vertical-axis tree is made up of a single vertical trunk, which serves to support many relatively small-diameter fruiting branches (Fig 15.3 and Plate 15.4). Maintaining the integrity of the apical bud of the leader during tree development is important for ensuring the development of weak fruiting branches (Lespinasse and Delort, 1986). At planting and during the development years, the leader is not headed back (Table 15.3). The weak-growing fruiting branches develop along the trunk in a manner dependent on the fruiting type of the cultivar. Fruiting branches are retained along the trunk from a height of 1 m upward. For trees on M.9, a good balance between vegetative growth and fruiting is usually obtained with 12 to 16 fruiting branches (Lauri and Lespinasse, 2000). The number and distribution of branches are controlled by pruning. As the tree matures, fruiting branches are periodically renewed after bending under the weight of the fruit, and hence do not become permanent scaffold branches (Plate 15.5). Heavy fruiting controls

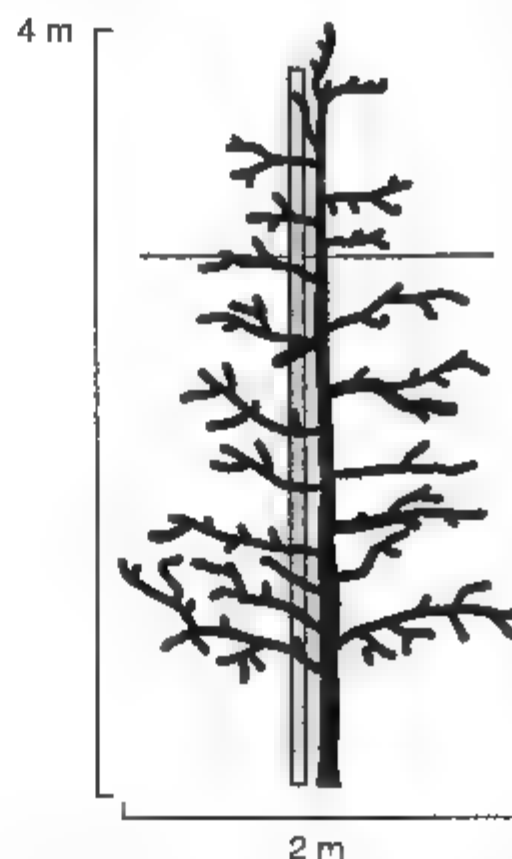


Fig. 15.3. The vertical-axis tree has a supported dominant trunk, a conic shape, a permanent basal tier of branches and small-caliper upper fruiting branches. Upper branches are shortened and then removed and replaced to maintain the conic shape.

Table 15.3. Simplified pruning and training plan for the vertical-axis system. (NB Northern-hemisphere dates.) (Adapted from Robinson and Hoying, 1994.)

First year	
At planting	Adjust graft union to 10 cm above soil level. Remove all scaffolds below 60 cm, using a flush cut. Trees with three or more scaffolds (25 cm long) should be headed at 110 cm above the soil line, with all scaffolds headed by removing one-third their length. Trees with fewer than three feathers should be headed at 90 cm and all feathers removed, using a bevel cut, leaving a 2 cm stub.
1–2 cm growth	Rub off second and third buds below the new leader bud to eliminate competitors to the leader shoot. Deflower tree.
5–10 cm growth	Attach clothes-pegs to new side-shoots on leader to promote wide crotch angles.
Early summer	Install tree-support system that will allow tree to be supported to 3 m. Attach tree to support system with a permanent tree tie above first tier of scaffolds, leaving a 5 cm diameter loop to allow for trunk growth.
July	Tie developing leader to support pole with permanent tie. Remove clothes-pegs.
Second year	
Dormant	DO NOT HEAD LEADER OR PRUNE TREES. If additional scaffolds are needed, score above appropriate trunk buds at bud break.
10–15 cm growth	Pinch lateral shoots in top one-quarter of last year's leader growth, removing about 5 cm of growth (the terminal bud and four or five young leaves).
Mid-June	Repinch all lateral shoots in top one-quarter of last year's growth. Tie developing leader to support system with permanent tie. Remove all fruit on 1-year-old wood and hand-thin remaining fruits to 15 cm apart.
Mid-July	Repinch vigorous lateral shoots in top one-quarter of last year's growth. Tie down four or five permanent lower scaffold branches to the horizontal. Attach permanent trellis clips to tree to support fully second-year crop.
Third year	
Dormant	DO NOT PRUNE LEADER. Remove overly vigorous upright limbs that are more than two-thirds the diameter of the leader, using a bevel cut. Tie down other vigorous, upright limbs below the horizontal overlooked during second summer.
10–15 cm growth	Pinch lateral shoots in top one-quarter of last year's leader growth removing about 5 cm of growth (the terminal bud and four or five young leaves).
June 15	Repinch all lateral shoots in top one-quarter of last year's growth. Tie developing leader to support system with a permanent tie. Hand-thin to single fruits spaced 10 cm apart.
Mid-July	Repinch vigorous lateral shoots in top one-quarter of last year's growth.
August	Tie up lower scaffolds not expected to support the crop. Alternatively, do not tie up but prune back scaffolds to prevent limb breakage and preserve tree structure.
Fourth year	
Dormant	DO NOT HEAD THE LEADER. Remove overly vigorous upright limbs that are more than two-thirds the diameter of the leader, using a bevel cut. Tie down other vigorous, upright limbs below the horizontal overlooked during third summer.
Late May	Chemically thin, then follow up with hand-thinning to appropriate levels to ensure regular annual cropping and adequate fruit size.
August	Lightly summer-prune to encourage light penetration and maintain pyramidal tree shape. Tie leader to support system with a permanent tie at the top of the pole.
Fifth and sixth year	
Dormant	DO NOT HEAD THE LEADER. Shorten bottom-tier scaffolds where needed back to side-branch to facilitate movement of equipment and preserve fruit quality on lower limbs. In each year remove one of the least desirable lower-tier scaffold branches until only four remain. Shorten branches that have become pendant back to horizontal portion of the branch. Remove up to one vigorous upper-scaffold limb each year to begin renewal of fruiting branches.

Continued

Table 15.3. *Continued.***Fifth and sixth year—Continued**

Late May	Chemically thin, then follow up with hand-thinning to appropriate levels to ensure regular annual cropping and adequate fruit size
August	Lightly summer-prune to encourage light penetration and maintain pyramidal tree shape
Mature-tree pruning	
Dormant	Limit tree to desired height by cutting leader back to a fruitful side-branch. Shorten bottom-tier scaffolds by pruning back to side-branch to facilitate equipment movement and preserve fruit quality on lower limbs. Remove one or two vigorous upper-scaffold limbs each year, preserving all weak-fruiting wood and permanent lower-tier scaffolds
August	Summer-prune to encourage light penetration and maintain pyramidal tree shape

vegetative growth in the top, guaranteeing a uniform and moderate growth vigour in all parts of the tree. This helps maintain a natural equilibrium between fruiting and vegetative growth. The growth of the leader is naturally weakened by fruiting in the third and fourth years, causing it to bend under the weight of fruit, limiting its height. By the time this happens, trees have usually reached a height of 3–3.5 m.

Lespinasse and Delort (1986) identified three fruiting zones in fruiting limbs. 'Zone A' (0–30° from the vertical) is characterized by the development of strong vegetative shoots, which are able to bear fruits of good quality 1–2 years later. 'Zone B' (30° and 120° from the vertical) is the prime fruiting zone, with moderate shoot growth. 'Zone C', which is below 120°, produces smaller inferior fruits because of the deleterious effects of within-tree shading on fruit quality. The vertical-axis training system aims to develop limbs in zone B, which produce the best fruit quality. When a fruiting branch develops, it usually has a vertical orientation (zone A). If it is left unpruned, generally it will bend into zone B, with heavy cropping in the second or third year. If the branch becomes too pendant (zone C) from repeated fruiting, it is removed and a renewal branch is developed in its place. This system of pruning, therefore, keeps fruiting on relatively young organs, i.e. 2- to 3-year-old spurs and crowned brindles.

The vertical-axis system was embraced by French growers in the 1980s and by North

American growers in the 1990s and has now become the dominant orchard system in many parts of the world; however, many growers have made modifications to fit their commercial orchards (Granger and Phillon, 1988; Maillard and Herman, 1988; Rice, 1988; Tukey, 1988; Barritt, 1992; Perry, 1994, 1998; Barden, 1995; Quamme and Geldart, 1995; Robinson *et al.*, 1996a; Karasiewicz, 1997). The primary modification from the original vertical-axis protocol of Lespinasse has been the development of a permanent tier of lower scaffold branches, which are not renewed. Other modifications include pinching of vigorous laterals to suppress their growth, shortening of fruiting branches to reduce sunburn, bending of the leader to reduce leader vigour, and replacing leaders with reproductive laterals on vigorous-growing trees (Perry, 2000). While these modifications have been introduced, the core of the original vertical-axis protocol is still followed by many growers today.

15.3.8 SolAxe system

In the mid-1990s, Lespinasse (1996) developed a modification of the vertical-axis, called the SolAxe, by focusing even more on branch bending and avoiding renewal pruning in an attempt to gain a more weeping canopy. Studies by Lauri and Lespinasse (1993) showed that the poor fruit characteristics of branches in zone C are due to the shading caused by other

branches kept above them. Additionally the A, B, C zone concept does not fit the terminally bearing cultivars (type IV, according to Lespinasse, 1977), such as 'Granny Smith' or 'Rome Beauty'. In these cultivars, the growing shoot generally ends in a fruit-bud and is able to develop a bourse shoot, which will fruit again the following year. To utilize this natural balance between vegetative growth and fruiting on type IV cultivars, they suggested a new fruiting-branch training concept, which did not utilize removal of pendant shoots back to more vertical renewal branches, but relied on the removal of the vertical renewal shoots to keep the pendant fruiting branch well exposed and productive. The name of the new system, SolAxe, was taken from the 'Solen' system, on which the new fruiting-branch concept was initially developed during the 1980s, and from the vertical-axis system. The system combines the bending of the central axis and the fruiting branches from the Solen system with the free-growing fruiting branches and the removal of competing vegetative branches from the vertical-axis system.

The tree is developed at planting by strongly bending the feathers along the trunk into an arc. Branches that are below 1.2 m are removed. The leader is attached to a support system either in the autumn of the first growing season or at the end of spring in the second season. The leader is left unheaded and allowed to grow to the top of the support system (Plate 15.6). When the leader reaches the top of the support system, it is bent horizontal, either naturally by fruiting or artificially by bending (Fig. 15.4). Upper fruiting branches are bent below the horizontal, either naturally through the weight of the fruits or artificially by tying during the second or third year. Excess branches are removed by pruning, beginning in the fourth year. As with the vertical-axis system, the best balance between vegetative growth and fruiting on a mature SolAxe tree is obtained with 12–16 fruiting branches arranged spirally along the trunk. On each fruiting branch, upright shoots are removed annually and the pendant portion is retained.

15.3.9 Slender-pyramid system

The slender-pyramid system was developed by Tustin and colleagues in the late 1980s in New Zealand (Tustin *et al.*, 1990; Tustin, 2000). In designing their system they considered physiological principles of light interception, light distribution and pruning, plus combined features of the vertical-axis, McKenzie central-leader and slender-spindle systems (McKenzie and Mouat, 1963; Wertherm, 1978a,b; Lespinasse and Delort, 1986). The slender-pyramid management system can be used with relatively low tree densities (600 trees ha⁻¹) with MM.106 rootstock and with moderately high tree densities (2000 trees ha⁻¹) with M.9. The slender-pyramid tree has a dominant central leader, a well-developed, spreading, basal tier of four branches bearing fruiting laterals, with a narrow pyramidal canopy above the basal tier (Fig. 15.5). The mid- and upper canopy is comprised of well-spaced whorls of weaker fruiting laterals arising directly off the trunk. Trees are not headed when planted and are supported using a single- or multiple-wire vertical trellis (Table 15.4). Unrestricted extension growth of the central leader is encouraged by removal of competing lateral shoots early in the summer each year.

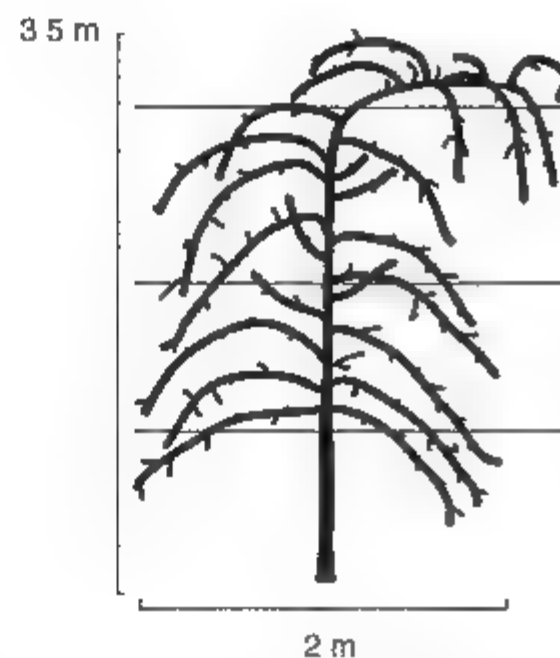


Fig. 15.4. The SolAxe tree has a supported dominant trunk, with all branches trained to a pendant position. Branches are not renewed. The upper part of the tree is bent horizontal to limit tree height and reduce vegetative growth in the top.

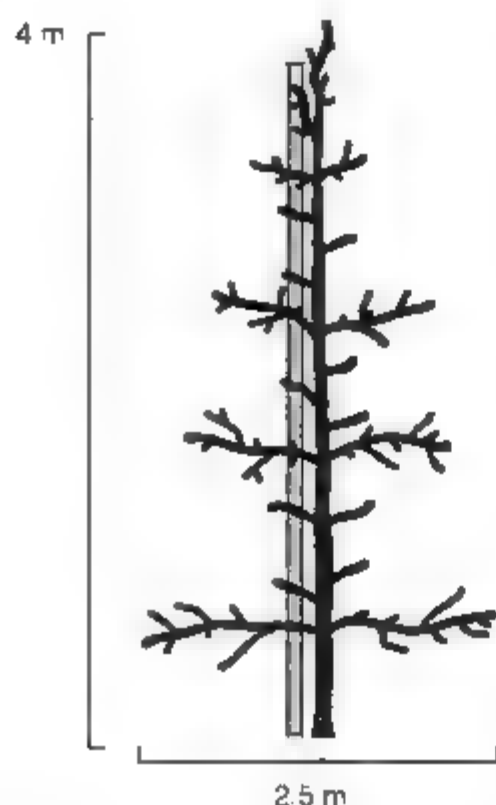


Fig. 15.5. The slender-pyramid tree has a supported dominant trunk, a conic shape and well-defined tiers of branches. A hierarchy of branch thickness is maintained from the bottom to the top of the tree by removing large-diameter branches in the upper part of the tree. Conic shape is maintained by shortening upper branches.

In the first year, the growth of six to eight basal-tier limbs is encouraged by early-summer removal of unwanted competing lateral shoots from the central leader. No further pruning in the first year is required. During the second year, basal tier limbs are spread down to 15–20° above the horizontal. Extension of the basal limbs is encouraged by ensuring that there is only a single apical shoot on each limb. In the second and third years, selection and thinning among lateral shoots arising from the central leader above the basal tier are done in early summer. In the second year, fruiting is allowed only when well-branched nursery trees are used and then only on spurs on the basal-tier limbs or directly on the central leader. This system results in rapid canopy development, with a hierarchy of fruiting branches of flat orientation and decreasing vigour up the central leader (Plate 15.7). From the third year, cropping increases rapidly, which limits continued expansion of the tree canopy. As the tree matures, the number of limbs in the basal tier is reduced progressively to an opti-

mum of four, arranged in a cruciform array across and along the row. Mature tree management utilizes renewal pruning for replacement of fruiting branches that are too vigorous or long to maintain a satisfactory light environment within the canopy

15.3.10 HYTEC system

The hybrid tree cone orchard system (acronym HYTEC) was developed in the late 1980s by Barritt (1991, 1992) specifically for arid apple-producing areas that have significant fruit sunburn. The system also has the goals of high, early and sustained yield per hectare, high labour efficiency and high fruit quality. It is a blend of the slender-spindle (Wertheim, 1978b) and vertical-axis (Lespinasse, 1980) systems that combines nuances of both systems and is intermediate in canopy height between the two (Barritt, 1992). In addition, techniques for vigour control and minimal pruning used with angled-canopy systems, such as the Tatura trellis, the Geneva Y trellis and the Güttinger V, are also incorporated into central-leader management of HYTEC trees. To reduce vigorous growth high in the tree (often a feature of mature vertical-axis trees), the central-leader of a HYTEC tree, during the formative years, is pruned and/or bent annually in a manner similar to that of the slender-spindle system. To achieve greater production at full canopy than slender-spindle trees, the HYTEC tree is taller with greater canopy volume, a characteristic of vertical-axis trees. Light distribution is maintained in the HYTEC tree by maintaining an open canopy structure. Fruit sunburn is also reduced on HYTEC trees by providing some limb-to-limb shading through stiffening lateral limbs with shortening pruning, a technique used with slender-spindle training, but not in the training of vertical-axis trees (Fig. 15.6)

Mature trees are 3 m tall and cone-shaped, with a central leader and a basal width of 1.5–2.25 m. Tree density is from 1400 to 2300 trees ha⁻¹, with spacing from 1.25 to 2.0 m between trees in the row and 3.5 to 4.25 m between rows. Each tree is supported with either a three-wire vertical trellis, an individ-

Table 15.4. Pruning and training plan for the slender-pyramid system (NB. Northern-hemisphere dates) (Adapted from Tustin, 2000.)

First year	
At planting	Adjust graft union to 10 cm above soil level. Remove all scaffolds below 60 cm, using a flush cut. DO NOT HEAD THE LEADER
5–10 cm growth	Remove vigorous shoots that are competitive with the leader
Early summer	Install tree-support system that will allow tree to be supported to 3 m. Attach tree to support system with a permanent tree tie above first tier of scaffolds, leaving a 5 cm diameter loop to allow for trunk growth
Second year	
Dormant	DO NOT HEAD THE LEADER. If additional scaffolds are needed, score above appropriate trunk buds at bud break
5–10 cm growth	Remove vigorous shoots that are competitive with the leader
Early summer	Limit cropping to spurs close to the base of the basal-tier limbs
Mid-July	Tie down four to six permanent basal-tier scaffold branches to 15° above horizontal
Third–fifth year	
Dormant	DO NOT HEAD THE LEADER. Remove overly vigorous upright limbs that are more than two-thirds the diameter of the leader, using a bevel cut
5–10 cm growth	Remove vigorous shoots that are competitive with the leader
Early summer	Remove lateral shoots that are excessively vigorous, have narrow crotch angles or are in poor positions. The branches along the leader of the tree should have a hierarchy of decreasing vigour up the leader
Fourth–sixth year	
Dormant	DO NOT HEAD THE LEADER. Remove overly vigorous upright limbs that are more than two-thirds the diameter of the leader, using a bevel cut. Progressively reduce the number of basal-tier branches to an optimum of four arranged in a cruciform array across and along the row, by removing one each year
5–10 cm growth	Remove vigorous shoots that are competitive with the leader
Early summer	Remove lateral shoots that are excessively vigorous, have narrow crotch angles or are in poor positions. The branches along the leader of the tree should have a hierarchy of decreasing vigour up the leader
Mature-tree pruning	
Dormant	Remove and renew upper-scaffold limbs when they cause excessive shading and to develop new fruiting wood. Limit tree to desired height by cutting leader back to a fruitful side-branch. Shorten bottom-tier scaffolds by pruning back to side-branch to facilitate equipment movement and preserve fruit quality on lower limbs
August	Summer-prune to encourage light penetration and maintain pyramidal tree shape

ual post or a thin bamboo or metal conduit pole secured to a single-wire-trellis support system. The support is used to train the tree vertically and to prevent tree leaning and/or breakage during strong winds and with heavy crops. The most common rootstocks for non-spur cultivars are M.9, B.9 and M.26 (Barritt *et al.*, 1995). Annual pruning or bending of the central leader – a decision based on central-leader vigour – encourages the development of strong lower-tier scaffold branches, stimulates branching and reduces tree height

in a manner similar to slender-spindle tree training. The lower tier of horizontal scaffold limbs is permanent. Scaffold branches are shortened to fit within their allotted space by pruning to a weak lateral or spur. Upper limbs are trained horizontally and, after bearing fruit, are shortened into older wood to retain the tree's cone shape, to stiffen limbs and to stimulate shoot growth, which provides transient shade that reduces fruit sunburn. Central-leader height is limited to 3 m by pruning into older wood to a weak lateral.

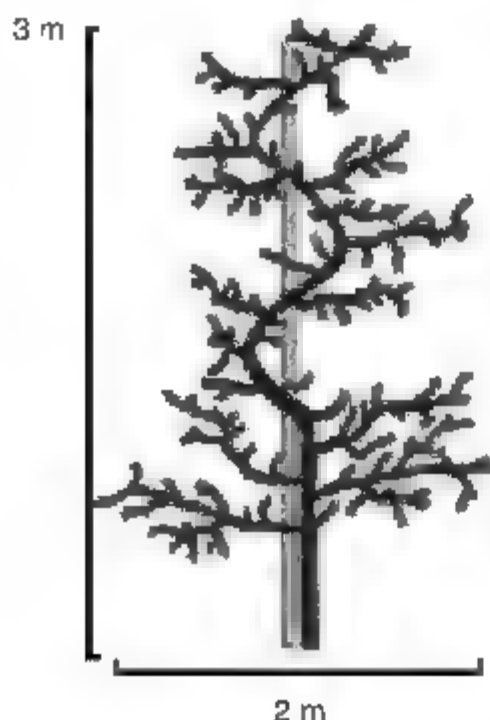


Fig. 15.6. The HYTEC tree has a supported zigzagged trunk, a conic shape and a permanent basal tier of branches. Upper branches are shortened to stiffen them to prevent movement with fruit load. Large upper branches are removed.

At planting, unbranched trees (whips) are pruned at 80–90 cm above the soil and branched (feathered) trees are pruned at about 25 cm above the top useable branch, which is usually 90–115 cm above the soil (Table 15.5). Branches that are longer than about 50 cm are headed lightly up to one-third their length to stiffen the branches, to reduce blind wood and to reduce top : root ratio and thus lessen transplant shock. Branches are trained to an angle between horizontal and 30° above the horizontal.

The HYTEC system utilizes pruning and/or bending techniques for training the central leader to ensure adequate branching along the leader and to control vigour in the top of the tree. In some climates, an unpruned central leader produces excessive growth and insufficient lateral branches. The few lateral branches that develop are below the terminal bud and are narrow-angled shoots. A 0.5–1 m section of the central leader may be without lateral branches. With the HYTEC system, it is essential to assess central-leader vigour before deciding on the appropriate management procedure. The central leader of HYTEC trees can be either: (i) lightly or moderately pruned by heading; (ii) left unpruned and trained verti-

cally; or (iii) left unpruned and bent at a 45° angle (Barritt, 2000) (Plate 15.8). Heading can be used if central-leader growth is weak (generally less than 50 cm in length), to encourage stronger growth and stimulate branching. At intermediate vigour levels (between 50 and 100 cm of growth), the central leader can be left unpruned as there is a need neither to stimulate branching by heading nor to reduce vigour. With excessive vigour levels (generally more than 100 cm in length), bending of the central leader is used to reduce tree height and to stimulate branching. Bending or zigzagging the central leader is a hybrid technique that falls between the vertical-leader training of the vertical-axis system and the angled leader of systems such as the Tatura trellis, the Geneva Y trellis or the Güttinger V. Angling the leader at 45° reduces extension growth; however, the whole tree is still orientated vertically. The zigzag technique reduces tree-height extension and stimulates lateral branching. Until the tree reaches its final height of 3 m, a decision about central-leader training must be made each dormant season. The decision is based on the vigour of the central leader. Therefore, it may be necessary to bend the central leader in one year if it has had very strong growth, but in the next season, if growth is moderate, the appropriate central-leader-training technique will be to tie it vertically and avoid any other intervention. When the tree exceeds a height of 3 m, the leader is cut back into older fruiting wood to a weak horizontal branch.

The lower-tier scaffold limbs are permanent and are trained horizontally or at a slight upward angle ($< 30^\circ$). Other lateral branches are trained horizontally and are maintained within their allotted space by shortening into older wood, usually to a weak lateral or spur, either in the dormant season or during the summer. Shortening pruning is used to stiffen limbs. Stiff limbs have less fruit sunburn than flexible limbs, which change position during the season as fruit weight increases. The additional branching induced behind the shortening cut also provides temporary (transient) shade, which reduces fruit sunburn. Limbs are usually shortened following their third

Table 15.5. Pruning and training plan for the HYTEC system (NB. Northern-hemisphere dates.) (Adapted from Barritt, 2000)

First year	
At planting	Adjust graft union to 10 cm above soil level. Remove all scaffolds below 60 cm, using a flush cut. Trees with three or more scaffolds (25 cm long) should be headed at 110 cm above the soil line. Branches longer than 50 cm should be headed by removing one-third their length. Trees with fewer than three feathers should be headed at 90 cm and all feathers removed, using a bevel cut, leaving a 2 cm stub
1–2 cm growth	Rub off second and third buds below the new leader bud to eliminate competitors to the leader shoot. Deflower tree
5–10 cm growth	Attach clothes-peggs to new side-shoots on leader to promote wide crotch angles
Early summer	Install tree-support system that will allow tree to be supported to 3 m. Attach tree to support system with a permanent tree tie above first tier of scaffolds, leaving a 5 cm diameter loop to allow for trunk growth
July	Tie developing leader to support pole with permanent tie. Remove clothes-peggs
Second year	
Dormant	Bend leader to a 45° angle and attach to the support pole
Mid-July	Tie down four or five permanent lower-scaffold branches to slightly above the horizontal
Third year	
Dormant	Bend leader to a 45° angle in opposite direction of the bend from the previous year and attach to the support pole. Remove overly vigorous upright limbs that are more than two-thirds the diameter of the leader, using a bevel cut. Tie down other vigorous, upright limbs below the horizontal overlooked during second summer
August	Shorten lower-scaffold branches to allotted tree spacing and to prevent limb breakage to preserve tree structure
Fourth–sixth year	
Dormant	Bend leader to a 45° angle in opposite direction of the bend from the previous year and attach to the support pole. Remove overly vigorous upright limbs that are more than two-thirds the diameter of the leader, using a bevel cut. Tie down other vigorous, upright limbs below the horizontal overlooked during third summer. Shorten horizontal fruiting branches to stiffen them and limit their length
August	Lightly summer-prune to encourage light penetration and maintain pyramidal tree shape
Mature-tree pruning	
Dormant	Limit tree to desired height by cutting leader back to a fruitful side-branch. Shorten bottom-tier scaffolds by pruning back to side-branch to facilitate equipment movement and preserve fruit quality on lower limbs. Shorten upper branches to maintain cone shape. Periodically remove an upper branch that has become too large and vigorous
August	Summer-prune to encourage light penetration and maintain pyramidal tree shape

year of growth and may be shortened again in subsequent years. Eventually upper limbs are completely removed. The decision to remove a limb is based on the amount of shading it causes lower in the tree canopy and its vigour. To improve canopy openness and light distribution, limbs are usually removed when their diameter is 50% of the diameter of the central leader at the point of attachment (Barritt,

2000). If shading of the lower canopy reduces flowering, fruit set, fruit size and colour to unacceptable levels, limbs higher in the tree must be removed, regardless of their diameter. A short stub is retained as a site for a new replacement shoot. At maturity, a row of HYTEC trees, when viewed from the side, should have a sawtooth pattern between tops of adjacent trees.

Once a HYTEC tree reaches full canopy size, maintenance pruning includes: (i) shortening pruning of the central leader (to limit tree height), the upper branches (to maintain the cone shape) and the permanent lower scaffold branches (to limit tree width); (ii) periodic removal of upper limbs to renew fruiting branches and improve sunlight distribution; and (iii) removal of unwanted shoots, including forked branches and vigorous upright shoots.

15.3.11 Super-spindle system

The modern version of the super-spindle system or cordon system was developed in southern Germany by Nüberlin in the early 1990s (Weber, 2000). However, the fruit-wall system developed by Luckwill (1978) at Long Ashton research station was an earlier version of the super-spindle system that relied on the use of growth-regulating and flower-regulating chemicals to limit tree size and induce heavy cropping. The German super-spindle system is a modification of the slender-spindle system that utilizes very high tree densities and draws upon the concepts of the 'Bleiber-Weicher' planting system, which was originally developed by Dickenmann, a nurseryman in Switzerland. That system suggested planting compact, slim apple trees with spurs along the central leader at very close spacings, in single rows and then pulling out every second tree after 4 or 5 years once canopies became too crowded. Nüberlin suggested leaving the trees at the original planting distance throughout the life of the orchard and developing management strategies to keep the trees compact without the development of thick lateral branches (Nüberlin, 1993; Fig. 15.7 and Plate 15.9)

The goals of the super-spindle system are very early and high yields so that new cultivars can be introduced as quickly as possible to meet market demands, less manual work, less chemical input and high picking output, resulting in low fruit cost per hour of labour. No exact definition exists of what a super-spindle orchard is. Österreicher (1993) classified the different systems according to their

tree diameter. The slender-spindle has a diameter of 1.0–2.0 m, the super spindle 0.5 to 1.0 m and the string tree less than 0.5 m. Most commercial super-spindle orchards have a row spacing of 3 m or less and a planting distance within the rows of 45–80 cm, giving a density of 4000 to 7500 trees ha⁻¹. Row distances less than 3 m can be too narrow to obtain high picking outputs. Mature tree height is 2.5–2.75 m.

The super-spindle system has a goal of some production during the first year in the orchard. This can best be achieved with nursery trees that have some flower buds (generative trees). Often growth-regulator treatments of multiple low-dose sprays of naphthaleneacetic acid (NAA) or ethephon are applied in the nursery row to stimulate flower-bud production of lateral buds on 1-year wood. Super-spindle orchards do not usually use the highly branched and relatively expensive trees used in slender-spindle orchards, but rather whips with a number of short shoots along the leader or even cheaper trees, such as budded rootstocks (sleeping-eye trees) (Weber, 1997).

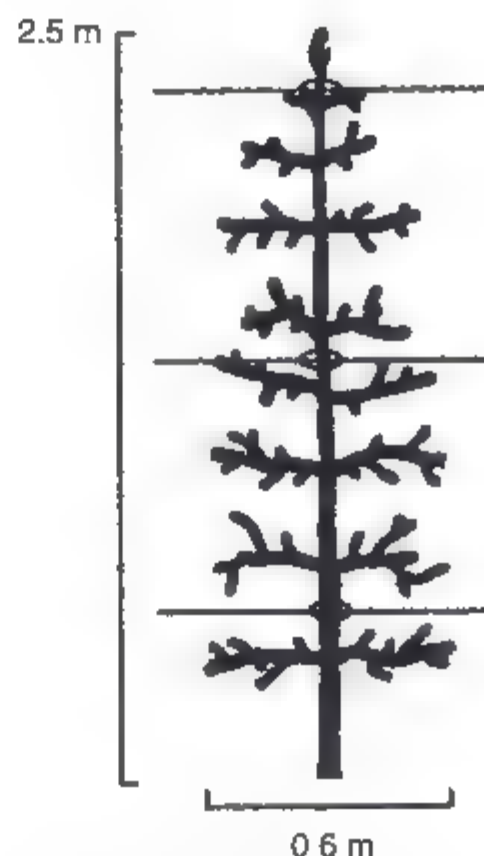


Fig. 15.7. The super-spindle tree has a supported trunk, a narrow cylindrical shape and no permanent branches. Vigorous branches are removed, leaving only small-diameter fruiting branches on the trunk.

Because of the very high total tree costs per hectare due to the high tree densities of this system, most growers grow their own trees to reduce the cost of plant material.

Super-spindle trees are trained differently from slender-spindle trees (Table 15.6). To reduce tree growth and maximize early fruiting, super-spindle trees are not headed at planting and are often planted on top of the ground and a small amount of soil is pushed up to cover the roots. In the first year, the steep-angled and strong lateral branches (larger in diameter than half the size of the central leader) are removed by ripping them from the tree. Growth-regulator sprays of NAA or ethephon can also be used to stimulate flower-bud initiation. In the second year, no significant pruning is done. In the third year, weak shoots are cut back into 2-year-old wood to promote shoot strength. Water sprouts are removed through ripping. In the fourth year, weak shoots are cut back into 2-year-old wood and tree height is limited by one single cut into 2-year-old generative wood.

The orchard life of super-spindle orchards can be as short as 7 years, but generally not longer than 12–15 years. This means that the economic success of super-spindle orchards depends to a large extent on very early, high yields of a high-priced new cultivar, low-priced trees from the nursery, higher picking output and fewer management hours to maintain the system. Fixed costs for the establishment of a super-spindle orchard are higher than for other systems and must be justified by the market returns of the cultivar and the early yields. The high cost of the system makes it a riskier system than more moderate-density systems. However, if there is an economically friendly market situation with a new high-priced cultivar that has good fruit size and a non-biennial bearing habit, coupled with inexpensive plant material, profitability for a new super-spindle orchard can be achieved in a short time period. This permits a short orchard lifetime, which gives growers flexibility to respond to new cultivars and changes in market demand of existing cultivars.

15.3.12 Meadow-orchard system

The meadow-orchard system was developed by Hudson (1971) and Luckwill (1978) as the ultimate in apple-orchard intensification with trees planted at a density of 70,000 trees ha⁻¹. The trees are spaced 30 cm × 45 cm and have a tree height of 1 m. The orchard is managed like an agronomic crop, with all of the machinery work done over the row. The system is based on an alternate-year cropping schedule and mechanization of harvest. The orchard is developed by planting a budded rootstock and, during the first year in the orchard, treating the developing shoot with growth- and flower-regulating chemicals to induce flowering. The tree is allowed to crop in the second year and produces from seven to 13 fruits. At harvest the entire top of the tree including the fruit is cut off with a mechanical harvester/combine and the fruit is separated from the tree top. The 2-year cycle is then repeated. Several rootstocks can be used, such as M.26 and MM.106. Because of the very high tree density, this system is based on having very cheap trees, which would probably have to be propagated by hardwood cutting and would be own-rooted. Very high experimental yields of 100 t ha⁻¹ were achieved, but only every other year. This system was never planted commercially with apples, but commercial versions were established with peaches.

15.3.13 Advantages and disadvantages of conic-shaped systems

Conic-shaped systems are currently the dominant tree form in commercial orchards in most parts of the world. The primary advantages of the conic shape are as follows:

1. It is a natural tree form for apple that does not require extensive branch and leader manipulation to produce and is easy to manage. This allows trees to be developed with minimal labour for tree training.
2. Its shape gives good light distribution throughout the canopy by limiting the width of the top of the tree. This results in minimal shading by the upper limbs of the lower limbs.

Table 15.6. Pruning and training plan for the super-spindle system (NB. Northern-hemisphere dates) (Adapted from Robinson and Hoying, 1994.)

First year	
At planting	Plant tree with as much of the rootstock shank out of the ground as possible, while still covering all main brace roots, and tamp soil around roots. Remove all scaffolds below 50 cm, using a flush cut. DO NOT HEAD LEADER Prune off only diseased and broken scaffolds. Provide trellis support immediately and tie tree to bottom wire
Late June	Spray trees with low doses of NAA three times spaced at 2-week intervals, to stimulate flower-bud formation for the second leaf
Second year	
Dormant	DO NOT HEAD LEADER. DO NOT PRUNE
Early June	Hand-thin crop to single fruits 10 cm apart
Late June	Spray NAA at 5 p.p.m. three times, spaced at 2-week intervals, to stimulate flower-bud development for the third leaf. Attach developing leader to second wire
August	Attach permanent trellis clips to tree to support fully second-year crop
Third year	
Dormant	DO NOT PRUNE LEADER
Late May	Chemically thin according to crop load, tree strength and weather conditions, then follow up with hand-thinning to appropriate levels to ensure regular annual cropping and adequate fruit size
Late June	Break vigorous shoots but leave attached to tree
August	Prune out excessively vigorous shoots with a bevel cut. Lightly summer-prune to encourage good light penetration and fruit colour
Mature-tree pruning	
Dormant	Clip out by hand excessively large and vigorous shoots (if diameter is > 50% that of the leader), particularly in the top, where regrowth is not wanted. Prune out excessively vigorous shoots (if diameter is > 50% that of the leader) in the bottom with a bevel cut where new shoots are wanted. Shorten pendant shoots to a fruit bud to keep the tree within its space, if needed
Late May	Chemically thin according to crop load, tree strength and weather conditions, then follow up with hand-thinning to appropriate levels to ensure regular annual cropping and adequate fruit size
August	Summer-prune to encourage good light penetration and fruit colour by cutting out vigorous shoots and shortening back horizontal shoots to first fruit

The primary disadvantages of conic-shaped systems are as follows:

1. A substantial amount of light energy falls between the tree rows on the tractor alleyways and is wasted. This energy could be used to produce fruit. The only way to reduce the wasted sunlight energy is to plant rows very close together or to increase tree height. Close row spacings, such as are used in the meadow orchard or the super spindle, require growers to purchase new narrow equipment. Many growers who want to plant dwarf trees are sometimes hesitant to purchase new equipment and consequently choose to plant conic-shaped trees with

wider than optimum row spacings to allow the use of existing equipment. This has resulted in relatively low yields for many dwarf orchards. Alternatively, if growers choose to plant wider than optimum row spacing, they should grow taller trees, which capture more light.

2. As conic-shaped trees mature, the upper branches of the tree begin to outgrow the lower branches, causing excessive shade on the lower canopy. Often the shape of mature trees resembled an inverted pear and eventually trees took on an umbrella shape. The central-leader system during the 1970s and 1980s had this problem when the upper tiers of branches were considered permanent.

Systems that have emphasized renewal of upper branches, such as the vertical-axis and slender spindle, have been more successful in maintaining the conical shape throughout the life of the tree

Over the last 50 years the majority of apple growers in the world have opted to plant one of the conic-shaped systems. In the 1960s and 1970s, the central-leader system was the most common system in the world. However, in Europe, the slender spindle and the vertical axis were the most common systems in the 1970s and 1980s. At the end of the 20th century, the most common systems are the slender spindle and its variants and the vertical axis and its variants. The slender spindle is most common in northern Europe and the vertical axis or one of its variants is most common in southern Europe, North America, South America, New Zealand, Australia, South Africa and Japan. Over the last decade, the height of most slender-spindle trees has increased to close to 2.75 m and thus the trees are more similar to vertical-axis trees. This has allowed slender-spindle orchards to intercept more light and achieve higher yields, while reducing the amount of pruning required to contain the tree to a short stature of 2 m. Likewise over the last decade, the planting density of vertical-axis orchards has increased from 1500 to more than 2000 trees ha⁻¹, which is similar to the density of slender-spindle orchards. Thus the evolution of the two leading systems in the world has resulted in great similarities between the systems. In a few locations in the world where land prices are very high or where there are subsidies from the government, the super-spindle system, with its very high tree densities, is being planted.

15.4 Flat Planar Canopy Systems

European gardeners have utilized trellises to restrict apple tree canopies to a two-dimensional plane for centuries and have developed artistic apple trees of many geometric shapes (Huggard, 1980). The most common

of these were the espaliers grown along walls and fences. The first commercial apple orchards with restricted two-dimensional-plane canopies were developed by Italian fruit growers in the mid-1950s, which they called the palmette training system. Their motive was to improve orchard labour efficiency by the use of platforms, which allowed more efficient picking, pruning and thinning of the palmette trees compared with the traditional vase-shaped fruit trees of that time. With the use of platforms to position workers near their work (pruning and picking), labour efficiency can be improved by 15–20%. The success of the palmette system stimulated widespread grower adoption in Italy. Italian research with this system led to significant technical innovations in pruning to hasten fruit bearing and reduce pruning costs over the life of the orchard and to increased planting densities to reap the benefits of earlier and greater returns (Sansavini, 1983). A number of variations of the palmette system have been developed. Most of the newer palmette systems utilize dwarfing rootstocks, which were not part of the original palmette system. The suitability of the palmette system to the use of picking platforms helped it gain widespread acceptance in Italy in the 1960s and 1970s, but, as the use of dwarfing apple rootstocks became common in the 1980s and 1990s, the advantage of picking platforms disappeared

15.4.1 'Regular' palmette system

The original or 'regular' palmette training system was developed by Baldassari, a fruit grower in Ferrara, Italy, in the mid-1950s (Sansavini, 1993). The tree is trained to a 3 m tall four- to six-wire vertical trellis, which serves to support the tree and crop at maturity. The palmette tree has a central trunk and regular tiers of branches that are trained to the two-dimensional vertical plane along the row. Branches that are not in this plane are removed or trained over to the wire trellis in the row plane. The branches at each tier are tied either at an oblique angle (30°), so that they grow up across the wires (oblique palmette) (Fig. 15.8), or horizontally along

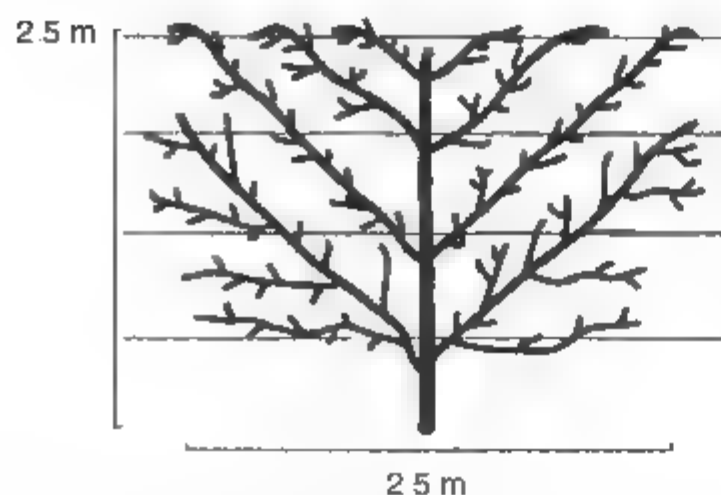


Fig. 15.8. The oblique-palmette tree has a central trunk with four or five tiers of permanent scaffold branches, which are trained at a 45° angle above horizontal oriented along the row, forming an overlapping lattice structure between trees along the row

the wire at each tier (horizontal palmette) (Fig. 15.9 and Plate 15.10). The most common rootstocks used with this system are MM.106, MM.111 and M.7 (Rosati, 1978). Tree spacing is 3.5–4 m in the row and 4–5 m between the rows (Corelli-Grappadelli, 2000). Tree height is usually 4–5 m. The palmette system has also been adapted to smaller trees on M.9 with dimensions shown in Figs 15.8 and 15.9. With the early versions of palmette orchards, the tree was formed by annual heading cuts to the leader for the first several seasons, to obtain a very regular tree structure, with four to six tiers of either oblique-angled or horizontal branches. This

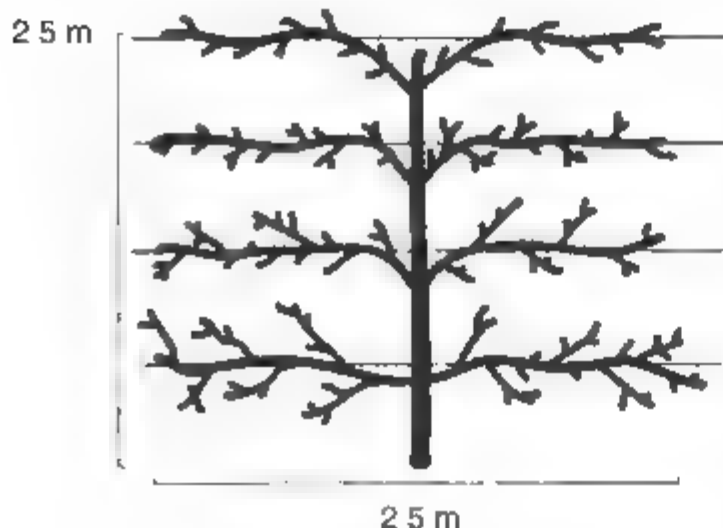


Fig. 15.9. The horizontal-palmette tree has a central trunk with four or five tiers of horizontal scaffold branches trained along the wires down the row. A hierarchy of branch diameter is maintained from the bottom to the top of the tree by removing large-diameter branches in the top.

style of pruning delayed the onset of production because of the heading cuts. Later versions of the palmette system used feathered trees ('anticipated' or 'sprint' palmette) from the nursery, where the feathers could be used to form the lower tier of branches without the use of heading cuts.

15.4.2 'Free' palmette system

The 'free' palmette system is a variation of the regular palmette system, but without its rigid structure, allowing the formation of branches from laterals emerging from the trunk without any geometric pattern. With this system, heading cuts at planting and thereafter are avoided, unless the tree needs to be reinvigorated. Early versions of the free palmette also utilized semi-vigorous rootstocks, such as MM.106, but modern versions utilize dwarfing rootstocks, such as M.9 or M.26, and higher tree densities. Common tree spacings are 1.5–2.5 m in the row and 3–4 m between the rows. This gives a planting density of 1000 to 2200 trees ha⁻¹. The trees are supported by a 3 m tall four- to six-wire trellis. Large, well-feathered trees are usually used. If feathered trees are used to develop the palmette system, then the tree is planted without heading cuts (Table 15.7). Some of the feathers that are not in the plane of the palmette (row plane) are removed and the first tier of branches is selected from the remaining feathers. If the tree is not well feathered, a heading cut is performed at planting and the selection of the leader and the branches must be delayed until the second year. Heading cuts to the leader or lateral branches are avoided to hasten the onset of production. Summer pruning is used to correct the growth of the tree. The tree is allowed to grow freely in the first year after planting. If it grows fast and develops sufficiently, the second tier of branches can be selected during the first summer, or else the choice is postponed to the second growing season. Higher-tier branches are developed along the developing leader by growth regulators or bending and twisting instead of cutting. They are selected during the second and third growing seasons, depending on

Table 15.7. Pruning and training plan for the palmette-trellis system (NB. Northern-hemisphere dates) (Adapted from Robinson and Hoying, 1994.)

First year	
At planting	Adjust graft union to 10 cm above soil level. Remove all scaffolds below 50 cm, using a flush cut. If tree has no feathers, head leader at 60 cm or expected height of first wire. If the tree has two good feathers originating near expected height of the bottom wire, head at 110 cm above soil line or at expected height of second wire. Do not head scaffold branches.
1–2 cm growth	Rub off second and third buds below the new leader bud to eliminate competitors to the leader shoot. Deflower tree.
5–10 cm growth	Attach clothes-pegs to new side-shoots on leader to promote wide crotch angles.
Early summer	Install trellis support system with bottom wire at 60 cm and support posts every 15 m along row. Attach tree to bottom wire with a permanent tree tie, leaving a 5 cm diameter loop to allow for trunk growth.
July	Tie developing leader to second wire with permanent tie. Remove clothes-pegs. Choose two scaffolds on opposite sides of the trunk and tie to the bottom wire. Ensure that shoot tips remain at a slight upward angle.
Second year	
Dormant	If tree was headed to second wire in first year, skip to third-year training, otherwise head leader at 5 cm above second wire.
1–2 cm growth	Rub off second and third buds below the new leader bud to eliminate competitors to the leader shoot.
5–10 cm growth	Attach clothes-pegs to new side-shoots on leader to promote wide crotch angles.
July	Tie developing leader to third wire with permanent tie. Remove clothes-pegs. Tie bottom-tier scaffolds flat and attach to first wire with permanent ties. Choose two limbs on opposite sides of trunk arising at second wire and tie to second wire.
Third year	
Dormant	Head leader 10 cm above third wire. Remove unwanted, vigorous, upright shoots along the bottom scaffolds. Remove vigorous upright limbs that are competing with the leader.
1–2 cm growth	Rub off second and third buds below the new leader bud to eliminate competitors to the leader shoot.
5–10 cm growth	Attach clothes-pegs to new side-shoots on leader to promote wide crotch angles.
July	Tie developing leader to third wire with permanent tie. Remove clothes-pegs. Tie second-tier scaffolds flat and attach to second wire with permanent ties. Choose two limbs on opposite sides of trunk arising at third wire and tie to third wire.
Fourth year	
Dormant	Head leader 10 cm above fourth wire. Remove unwanted, vigorous, upright shoots along the bottom scaffolds. Remove vigorous upright shoots between tiers where necessary.
1–2 cm growth	Rub off second and third buds below the new leader bud to eliminate competitors to the leader shoot.
5–10 cm growth	Attach clothes-pegs to new side-shoots on leader to promote wide crotch angles.
July	Tie developing leader to fourth wire with permanent tie. Remove clothes-pegs. Tie third-tier scaffolds flat and attach to third wire with permanent ties. Choose two limbs on opposite sides of trunk arising at fourth wire and tie to fourth wire.
August	Lightly summer-prune scaffolds on bottom two wires.
Fifth and sixth year	
Dormant	Do not head the leader. Tie leader flat to the top wire in the fifth year and tie a vigorous shoot in the opposite direction in the sixth year. Remove vigorous, upright shoots. Remove upper-tier branches extending into the row, creating a flat fan arrangement above the first wire. Shorten bottom-tier scaffolds where needed back to side-branch to facilitate movement of equipment and preserve fruit quality on lower limbs.

Continued

Table 15.7. *Continued.***Fifth and sixth year—Continued**

July	Tie fourth-tier scaffolds flat and attach to fourth wire with permanent ties
August	Light y summer-prune permanent scaffold branches by removing upright shoots
Mature-tree pruning	
Dormant	Limit tree to desired height by cutting leader back to top wire. Shorten productive secondary branching on the bottom scaffold that extend into the alleys to facilitate movement of equipment and preserve fruit quality on lower limbs. Shorten branches on upper-tier scaffolds that extend out into the row to maintain narrow fan-shaped top. Annually remove and renew one of the largest-diameter limbs on the upper wires by tying a replacement shoot in its place
August	Summer-prune by removing vigorous, upright shoots throughout the canopy. Be sure to leave appropriate replacement shoots

the speed of development of the tree. The branches for each tier are selected to be 80–100 cm from the next lowest tier without complying to any geometric scheme. Selecting the branches in the summer has the advantage that they are easier to work with and will generally result in wider crotch angles. Selected branches are tied to the trellis, in the plane of the row direction. Often the upper branches are not permanent and are short-ended to allow light penetration and can be renewed every 3–4 years.

Mature-tree pruning consists of removing branches that extend across the row and keeping the canopy confined to a 2 m wide plane along the row. Upper-tier branches are renewed by removing one or two branches per year and allowing replacement branches to develop. Pruning the palmette is as quick as other systems (Sansavini *et al.*, 1980). If the canopy is kept narrow, with good light penetration, and the trellis helps maintain the shape throughout the life of the orchard, the tree may require less summer pruning than other systems (Corelli and Sansavini, 1989). However, the pruning of the palmette system cannot be neglected, as it too will develop excessive growth, particularly at the top, with all the disadvantages caused by shading.

The palmette system in its various iterations has enjoyed broad success in Italy and southern France, where it still holds an important place in the cultivation of many crops and is still the training system of choice for many growers. It is a leading system for peach in the Italian Romagna region (Corelli-Grappadelli, 2000), and continues

to be widely adopted in plums, sweet cherry and apricot (for the more vigorous cultivars). However, it is losing its edge to more intensive systems in apple and pear. In these crops, where growth can be more easily controlled by dwarfing rootstocks, the palmette is giving way to higher-density systems based on the spindle concept and its derivations (e.g. super spindle) or on Y- or V-shaped canopies (Sansavini, 1993; Sansavini and Corelli-Grappadelli, 1997).

15.4.3 Penn State thin-wall trellis system

The Penn State thin-wall trellis was developed by Tukey (1978) and is a modification of the regular palmette system. It uses a low 1.8 m tall four-wire trellis to allow all management operations to be done from the ground. It was also designed to be harvested mechanically and a prototype over-the-row harvester was built, which would comb the fruit off the trees. The system utilizes trees on dwarfing rootstocks, such as M.9 or M.26, spaced at 1.8–2.0 m within rows and 3.0 m between rows. The trellis has wires spaced 45 cm apart. At planting, the tree is headed near the lowest wire and, from the branches that develop below the heading cut, two scaffold branches are selected and trained in each direction along the row at an oblique angle (30°). The leader is headed annually at the next highest wire for the first 3 years and a pair of scaffolds are selected and trained at an oblique angle along the row. When the leader reaches the top wire, it is bent along

the row and tied to the top wire to become a horizontal scaffold branch on the top wire. A shoot arising from just below the top wire is trained in the opposite direction to form a second scaffold on the top wire. Each of the scaffold branches is allowed to grow until it reaches the trunk of the next tree in the row. The scaffold branches cross at the mid-point between trees, thus forming a permanent lattice of branches. The canopy develops into a continuous hedgerow. Mature-tree pruning consists of renewing the fruiting laterals that arise off the scaffold branches by cutting them back to the scaffold branch when they become too long. The width of the trellis hedgerow is determined by how long fruiting laterals are allowed to remain.

The Penn State thin-wall trellis has had limited commercial acceptance in the north-east of North America. It has been very successful with difficult-to-colour cultivars, such as 'McIntosh', where it has given the best fruit colour. However, the low mature-tree height has resulted in relatively low yields. With vigorous cultivars or soils, growers have had difficulty in controlling vigour in the tops of the trees as they age. The top horizontal scaffold branches have become excessively vigorous, producing many strong vertical shoots each year, which causes shading of the lower canopy. Although there have been some problems with this system, it does have high labour efficiency for pruning and hand-harvesting. It continues to find a place on pick-your-own farms, where the trellis can also be used to keep people picking in assigned rows.

15.4.4 Lincoln canopy system

The Lincoln canopy is a horizontal planar canopy system developed by Dunn and Stolp (1981) in New Zealand. The trees have a vertical trunk and a horizontal canopy at 1.5 m height (Plate 15 11). The width of the canopy is 1.2 m on each side of the tree row. Trees are spaced 2.4 m in the row and 4.25 m between rows. A 1 m gap between canopies of adjacent rows is maintained. The system was developed with semi-vigorous rootstocks, such as MM.106, but could be adapted to

dwarfing rootstocks with closer in-row spacings. This canopy system was designed to match the tree form to mechanical harvesters (Dunn and Stolp, 1987). A prototype mechanical harvester was built, which contacted the underside of the trellis, slightly raising it and allowing the fruit to fall to a catching and conveying surface below. The tree is developed by planting a large caliper and tall whip, heading the tree at 1.4 m and allowing four equal-diameter shoots to grow. Near the end of the first season, the four shoots are trained horizontally along the row (two in each direction) in the form of an H. These four shoots form the scaffold structure of the system. When vertical shoots that arise from the scaffolds are about 80 cm long, they are tied down to a horizontal position, perpendicular to the row direction. These shoots become the fruiting laterals of the canopy. The canopy system creates a very regimented and regular, single layer of fruiting laterals at 1.5 m high. By removing buds on the upper side of the laterals, most of the fruits are produced on down- or side-buds. This allows the fruit to hang free, which aids in mechanical harvesting.

Only a few commercial plantings of Lincoln canopy have been made. The horizontal position of all of the branches of the tree has the inherent physiological weakness of stimulating excessive shoot growth from the top of the canopy. This results in shading of the fruit and spurs within the canopy (Ferree *et al.*, 1989) and a diversion of significant biological resources to the production of unwanted shoot growth rather than fruit. Mechanical pruning was suggested by the inventors of the Lincoln canopy system to remove the crop of vigorous shoots from the top of the canopy. However, the indiscriminate cutting of a mechanical saw exacerbates this problem. The use of dwarfing rootstocks, such as M.9, would result in a lesser problem than the use of semi-vigorous rootstocks, such as MM 106.

15.4.5 Ebro trellis system

The Ebro trellis is a multi-tiered horizontal planar system developed by a New Zealand

commercial fruit-growing company in the late 1970s (Tustin *et al.*, 1989). The system utilizes an elaborate trellis structure with four horizontal tiers of wires stacked on top of each other and spaced 0.5 m apart, with the lowest tier at 0.9 m high and the top tier at 2.4 m. Each tier of wires has six strands of wires (three on each side of the tree) spaced 25 cm apart, giving a total width of the trellis of 1.5 m. Trees are planted at 2.4 m in the row and 3.6 m between rows. The trees are trained with one or two vertical leaders up between the centre wires, with horizontal tiers of branches originating at each tier of wires. The original system utilized trees on semi-vigorous rootstocks, such as MM 106, but it has been adapted to trees on dwarfing stocks, such as M.9, in some parts of the world. The canopy is developed by planting large caliper and tall whip trees, which are headed at the height of the first tier of wires at planting. A new leader and four lateral shoots of equal diameter are allowed to grow. Near the end of the first season, the four lateral shoots are trained horizontally along the row (two in each direction) in the form of an H in a manner similar to the Lincoln canopy system. When vertical shoots that arise from the four scaffolds at each tier are about 30 cm long, they are tied down to a horizontal position, perpendicular to the row direction. These shoots become the fruiting laterals of the canopy. In the second, third and fourth seasons, the process of heading the leader, developing four scaffolds and then fruiting laterals is repeated at each additional tier. Once the canopy is mature, the fruiting branches are maintained by annual removal of the vertical shoots arising from the top side of the horizontal branches. The objective is to develop a compact, efficient, high-yielding orchard system that is adapted to the use of mechanical production aids.

Several hundred hectares of Ebro trellis orchard have been planted around the world. However, as the trees have matured the chief challenge has been maintaining adequate light exposure for the lower tiers of the trellis to maintain fruit colour and consistent cropping (Tustin *et al.*, 1989; Warrington *et al.*, 1996). In addition, vigorous shoot

growth from the top of the upper tier has been difficult to control. To improve the light-distribution characteristics of the Ebro trellis, several modifications were proposed: (i) widen the bottom layer and narrow the top layer to give a triangular cross-sectional view of the canopy; (ii) reduce the number of layers to three instead of four; and (iii) use dwarfing rootstocks and closer in-row spacing to reduce tree vigour and the amount of unwanted shoot growth. A grower in Long Island, New York, has been very successful with a modified Ebro trellis that incorporated all three design modifications.

15.4.6 Solen system

The Solen system was developed by Lespinasse (1989) for use with tip-bearing (Type IV) cultivars. The Solen system is a low-domed (umbrella-shaped) form of training. The system utilizes dwarfing rootstocks, such as M.9. Trees are spaced 1.5 m in the row and 4.5 m between rows. Mature tree height is 2.0 m. The trees are supported by a short two-wire trellis (wires at 1 m and 1.6 m). The trees are developed by heading the tree at planting at 1.2 m above the ground. Two main scaffold branches are developed below the heading cut and, late in the first year or in the middle of the second season, are bent down the row to the opposite direction from where they originate and tied to the top wire. The two scaffolds thus cross each other at a point over the tree trunk. Fruiting laterals are developed off the two scaffolds. With tip-bearing cultivars, these fruiting branches bend readily with the weight of fruit, forming a cascading wall of fruiting branches on each side of the trellis. Mature pruning consists of thinning out fruiting branches to open up the canopy to maintain good light exposure to all parts of the canopy and to renew the fruiting laterals. Although early results with this system showed high yields, most of the commercial plantings had lower yields than taller systems, such as the vertical axis. This system has limited commercial interest and only for tip-bearing cultivars.

15.4.7 Tabletop bed system

The tabletop bed system was developed by Preston (1978) and Palmer and Jackson (1977) at East Malling Research Station in England. It is a very high-density system that eliminates the tractor alleys from between the tree rows, leaving only a walking path. The beds can be from three to 14 rows wide with a tractor alley between beds. This system utilized the very dwarfing rootstock M.27. Spacing was 0.5–1.0 m between trees and 1.5 m between rows. Mature tree height was 1.5 m and the tree canopy resembled a table top. The trees were supported by a short trellis only 75 cm tall. The trees were developed by annually shortening the leader and 1-year laterals to one half of their length for the first 3 years. Because of the very weak growth habit with M.27 rootstocks, this style of pruning resulted in a shallow canopy of leaves and fruit around the central leader. After the third year, pruning consisted of thinning out branches to maintain good light exposure to all parts of the canopy. This system achieved very high production (55 t ha⁻¹) and light interception (80%), with good fruit quality by the second season (Palmer, 1988). Mature yields were very high, due to the high light interception. However, the very high cost of establishment of the system and the necessity of specialized equipment to control pests and manage harvest have limited the interest in this bed system. It has not been planted commercially.

15.4.8 Present status of flat planar systems

The primary advantages of flat planar systems are the ability to mechanize orchard management and picking operations. The palmette was widely adopted in Italy and France because of the improved labour efficiency provided by picking platforms. Despite the potential of completely mechanized harvest with two-dimensional systems, this goal has not been realized. Several prototype harvesters were built, but their cost and their small but significant fruit-damage level, coupled with the continuing adequate supplies of labour in most apple-producing areas in the world, have prevented their implementation.

A second advantage of planar canopies is that the thin two-dimensional canopy has good light distribution to all parts of the canopy. The planar vertical trellis systems (palmettes and Penn State trellis) have produced some of the best fruit quality of any system. However, the horizontal planar systems (Lincoln and Ebro) have often had the poorest fruit colour (Ferree *et al.*, 1989). The Lincoln canopy and the original Ebro trellis proved to have significant management problems, resulting in poor fruit quality, and were abandoned. Both systems had excessive shoot growth arising from the tops of the horizontal canopies, especially when semi-vigorous rootstocks were used.

Another advantage of planar trellis systems is that the tree training can be systematized. Training recipes can be developed where limb or branch training can be simplified and performed by unskilled labour. The trellis can serve as a template of tree shape.

The primary disadvantage of flat planar systems is that the labour costs to manipulate the canopy into a confined geometric shape are much higher than systems that are based on a more natural tree shape. Attempts to reduce tree-training costs have partially succeeded, as with the free palmette system. A second and more critical disadvantage is that most flat planar systems use relatively low tree densities, which limits early yield and profitability.

15.5 V-shaped Canopy Systems

Although V-shaped apple canopies have existed for centuries in European gardens, it was not until the 1970s that V-shaped fruit trees were popularized for commercial orchards by Chalmers and van den Ende (1975) with the growing system known as the Tatura trellis. The Tatura trellis system was originally developed for peaches to increase yields and to allow mechanical harvesting but was later adapted for apples (Chalmers *et al.*, 1978). A number of variations of the Tatura trellis have been developed. Most of the newer V systems now utilize dwarfing rootstocks. With all V systems, the objective has been to improve

yield by improving light interception and to improve fruit quality by improving light penetration to the centre of the canopy.

V-shaped orchard systems can be categorized by tree shape and branch-training protocol. There are two basic shapes of inclined canopies: Y-shaped trees, which have a vertical trunk and two opposing arms of the tree trained to either side of the trellis, and V-shaped trees, where the whole tree is leaned to one side of the trellis while the next tree in the row is leaned to the other side of the V trellis. Branch-training recipes of V systems can be categorized into two types: palmette and spindle. With the palmette type of branch training, the secondary branches are trained either flat along the wires or at an oblique angle across the wires, in both cases giving a flat two-dimensional fruiting plane for each arm. With the spindle type of branch training, the secondary branches are not trained to the wires and a three-dimensional cylinder or cone-shaped canopy is maintained around the main trunk.

15.5.1 Tatura trellis system

The Tatura trellis was developed by Chalmers and van den Ende (1975) and is a Y-shaped system with the arms of the trellis at 60° above the horizontal. Each tree has two main scaffold arms, and secondary branches are trained as a palmette. Semi-vigorous stocks, such as M.7, MM 106 and MM.111, are usually used. The trellis is 3 m high, with six wires per side. The trees are planted at close in-row spacings (1 m), typically with 5 m between rows. Trees are trained by heading the tree at 50 cm height at planting. Only two shoots are allowed to develop, with one trained to each side of the trellis. Secondary branches are trained at an oblique angle (45°) with respect to the main scaffold branch and are attached to the wires.

15.5.2 Mini-Tatura trellis system

The mini-Tatura trellis was developed by van den Ende and is similar to the Tatura trellis in shape and branch training, except

that dwarfing rootstocks, such as M.9 and M.26, are used and a much smaller trellis is needed (2 m high with four wires per side). The trees are planted at 1 m in-row spacings and 4 m between rows. Trees are trained in a manner similar to the Tatura trellis by heading the tree at 50 cm height at planting and allowing only two shoots to develop, with one trained to each side of the trellis. Secondary branches are trained at about 45° or, in some cases, 90° from the leaders (horizontal along the wires) and are attached to the wires.

15.5.3 Geneva Y-trellis system

The Geneva Y trellis was developed by Lakso (Robinson *et al.*, 1989) and is a Y-shaped system with the arms of the trellis at 60° above the horizontal (Plate 15.12). In contrast to the Tatura trellis, trees in this system have multiple scaffold branches on each side of the trellis, trained in a fan-shaped arrangement (Fig. 15.10). Dwarfing rootstocks, such as M.9, M.26 or M.9 interstems, are usually used. The trellis is 2 m high, with only three wires per side (Fig. 15.10). The trees are typically planted at 1.5–1.8 m in-row spacings and with 4 m between rows. At planting, trees are headed at 70 cm above the ground and six to ten side-shoots are developed (Table 15.8). Half of the branches are trained to each side of the trellis in a fan arrangement. Secondary branches are tied to the wires and are trained between the main scaffolds to fill in the fan on each side.

The optimum angle for the arms of the Geneva Y trellis was studied by Robinson (1992a, 2000a). Robinson found a broad optimum angle between 50° and 70° above the horizontal where yield was maximized when between-row spacings were wide. However, at the close in-row spacing of 3 m, the optimum angle was more vertical (between 65° and 70°). The optimum angle for fruit size was also around 60°, while fruit colour was best on the most vertical angles. The best yield efficiency was at intermediate angles of around 60°. An angle of 65–70° above the horizontal resulted in the best balance of vegetative growth, cropping and fruit quality.

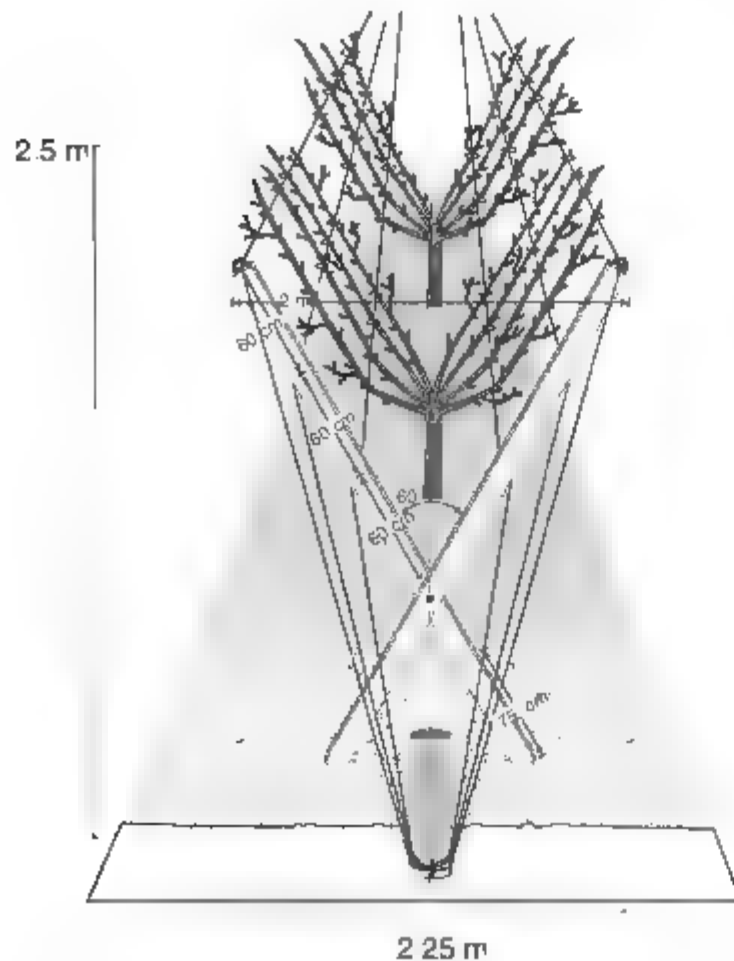


Fig. 15.10. The Geneva Y-trellis tree consists of a divided canopy with four or five equal-diameter branches trained to each side of the Y and no central trunk. Scaffold branches are attached to the wires of the trellis and spaced equally along the trellis. Large-diameter scaffolds are removed and replaced.

15.5.4 Mikado and Drilling systems

The Mikado and Drilling systems were developed by Widmer and Krebs (1997) and are Y-shaped systems, with the arms of the trellis at 70° above the horizontal. In the Mikado system, each tree has four scaffold branches of equal vigour (two on each side of the trellis) originating from a single trunk. Each scaffold branch is trained to a different quadrant of the trellis. With the Drilling system, each tree has three scaffold branches, with two trained to one side of the trellis and one to the other. This arrangement is alternated down the row. The trellis for both systems is 2 m high, with only one top wire per side and a single low wire at 30 cm above the ground running alongside the trunk. Four bamboo sticks for Mikado and three sticks for Drilling are attached near the trunk to the low wire and then at separate quadrant

points to the top wires. Scaffold branches are trained along the sticks. Dwarfing rootstocks, such as M.9 and M.26, are used. The trees are typically planted at in-row spacings of 1.8 m for Mikado and 1.35 m for Drilling and 3.5 m between rows. At planting, trees are headed at 70 cm above the ground and either three or four side-shoots are developed. Each scaffold branch is trained like the trunk of a slender spindle, with secondary branches arranged around the scaffold in a conic shape. The secondary branches are not tied to the wires.

15.5.5 MIA trellis system (A-shaped trellis)

The MIA trellis was developed by Hutton *et al.* (1987) and is a double-row V-shaped system, where arms of the adjacent rows of the trellis form an A-shaped canopy over the tractor alleyway (Plate 15.13). Workers have access to the centre of the V between the double rows. In many respects, it is a modification of the Tatura trellis, but the adjacent double rows are leaned over to the trellis, creating an A shape under which equipment travels. The double rows are planted 2 m apart, while the inter-row space beneath the canopy arms of the A shape is 6 m. The trees are planted at close in-row spacings of 1–1.5 m. Trellis arms are 60° above the horizontal and the trellis is 3 m high, with six wires per side. Semi-vigorous stocks, such as M.7, MM.106 and MM.111, are usually used. Since the whole tree is inclined over to the angled trellis at planting, large feathered trees are ideal and require very little pruning at planting. The main trunk is trained up the angled trellis and secondary branches are trained at an oblique angle (45°) from the trunk and are attached to the wires in a manner similar to the Tatura trellis.

15.5.6 Mini-V-trellis system

The mini-V trellis was developed by Tom Auvil of Washington State and is a V-shaped system that is similar to the mini-Tatura trellis, except that whole trees are leaned

Table 15.8. Pruning and training plan for the Geneva Y-trellis system (NB. Northern-hemisphere dates) (Adapted from Robinson and Hoyal, 1994.)

First year	
At planting	Adjust graft union to 10 cm above soil level. Remove all scaffolds below 40 cm, using a flush cut. Head leader to 60 cm or at the height of the expected base of Y-trellis frame
1–2 cm growth	Rub out the leader bud and attach clothes-pegs to ALL other new shoots to develop four to six equal-vigour scaffold branches. Deflower tree
5–10 cm growth	Attach clothes-pegs to new side-shoots on leader to promote wide crotch angles
Early summer	Install tree-support system and string a low training wire. Attach tree to training wire but leave scaffold shoots in an upright untrained position
July	Remove clothes-pegs
Second year	
Dormant	If fewer than six branches per tree developed in year 1, head sufficient scaffolds by removing two-thirds their length to produce a total of ten scaffold limbs. Assume three scaffolds will be created at each heading cut. DO NOT HEAD SCAFFOLDS if there are six or more suitable branches per tree. Remove overly dominant branches
Mid-July	Divide scaffolds and train one-half of them to each side of the Y, using a Max Tapener. Uniformly space scaffolds on each side of the trellis in a fan arrangement. If tips of trained branches are not upright, use string or rubber bands to tie in an upright position to ensure continued extension growth
Third year	
Dormant	DO NOT HEAD SCAFFOLDS. Remove shoots and suckers that are too low and not suitable for training to the wire
Mid-July	Attach scaffold limbs to the second and third wires, maintaining tips of branches in an upright position. Use permanent plastic trellis clips to attach scaffolds to first and second wires, making sure to maintain fan arrangement. Train new shoots to the trellis to fill existing gaps in the canopy. Remove unwanted upright sucker growth
Fourth year	
Dormant	Do not head scaffold limbs. Remove any low shoots or suckers that are not suitable for training to the trellis wires. Minimize pruning to encourage cropping
August	Attach scaffold branches to top wire, using trellis clips where necessary. Train suckers that will be used as replacement shoots to the bottom wire. Remove unwanted interior sucker growth
Fifth year	
Dormant	Minimize pruning. Where scaffold length is excessive, shorten scaffold length by cutting back to side-branches just above the top wire
August	Summer-prune by removing unwanted interior sucker growth. Retain one shoot on each side and train to the bottom wire to be used as replacement scaffolds
Mature-tree pruning	
Dormant	Begin limb renewal pruning by removing one or two scaffold limbs each year. Candidates for removal are those scaffolds that cause excessive crowding or are excessively long. Maintain a minimum 1.5 m open gap between scaffold tips of adjacent rows by the limb-renewal process and by shortening back long scaffolds to a suitable side-branch above the top wire
August	Summer-prune by removing unwanted interior sucker growth. Retain one shoot on each side and train to the bottom wire to be used as replacement scaffolds. Maintain a 1.5 m wide gap between rows by cutting back to suitable side-branches above the top wire

alternately down the row to each side of the trellis. The central leader of each tree is trained up one side of the trellis. Dwarfing rootstocks, such as M.9 and M.26, are used and trees are planted at 1 m in-row spacings and 4 m between rows. The trellis is identical to the mini-Tatura trellis. Since the whole tree is leaned to the trellis at planting, large feathered trees are ideal and require very little pruning at planting. The main trunk is trained up the angled trellis and secondary branches are trained at an oblique angle (45°) from the leader or in some cases at 90° from the leaders (i.e. horizontal along the wires) and are attached to the wires.

15.5.7 G ttingen V slender-spindle system

The G ttingen V was developed by Krebs (1988) and is a V-shaped system, with individual conic-shaped trees, that allows high tree densities without multiple tree rows (Mantinger, 2000). The trees are leaned alternately to each side of the trellis and are trained like conic slender-spindle trees (Fig. 15.11 and Plate 15.14). The trellis has an angle of 75° above the horizontal and has only one wire per side at 2 m high (Fig. 15.11). A 2.5 m steel, bamboo or wooden pole is placed in the ground beside the tree trunk and then leaned out to the wire (Hoying and Robinson, 1993). The trees are trained up the angled poles. Dwarfing rootstocks, such as M.9 and M.27, are used and trees are planted at 0.9 m in-row spacings and 3.5 m between rows. Since the whole tree is leaned to the trellis at planting, large feathered trees are ideal and require very little pruning at planting (Table 15.9). The main trunk is trained up the angled pole, using leader bending in a manner similar to a leaned slender-spindle tree. Secondary branches are not tied to the wires. The lower tier of branches is tied flat with strings, while upper branches are trained flat and kept shortened or renewed when too long. This keeps the tree in a cone shape for good light penetration.

15.5.8 V super-spindle system

The V super spindle is a very high-density version of the V slender-spindle system. Trees are planted at 0.5 m in-row spacings and 3.0 m between rows. The trees are leaned alternately to each side of the trellis, as with the V slender spindle (Plate 15.15). The trellis is also similar to the V slender spindle. Dwarfing rootstocks, such as M.9 and M.27, are used. Because of the very close in-row spacings, individual trees are trained similarly to the super-spindle system developed by Fritz Nuberlin. The ideal tree has medium calliper, with many short feathers, which are not pruned at planting. The main trunk is trained up the angled pole without leader bending, while secondary branches are not tied to the wires. Any large secondary branches that develop are removed and small secondary branches are allowed to crop and bend down. There are no permanent scaffold branches in the tree.

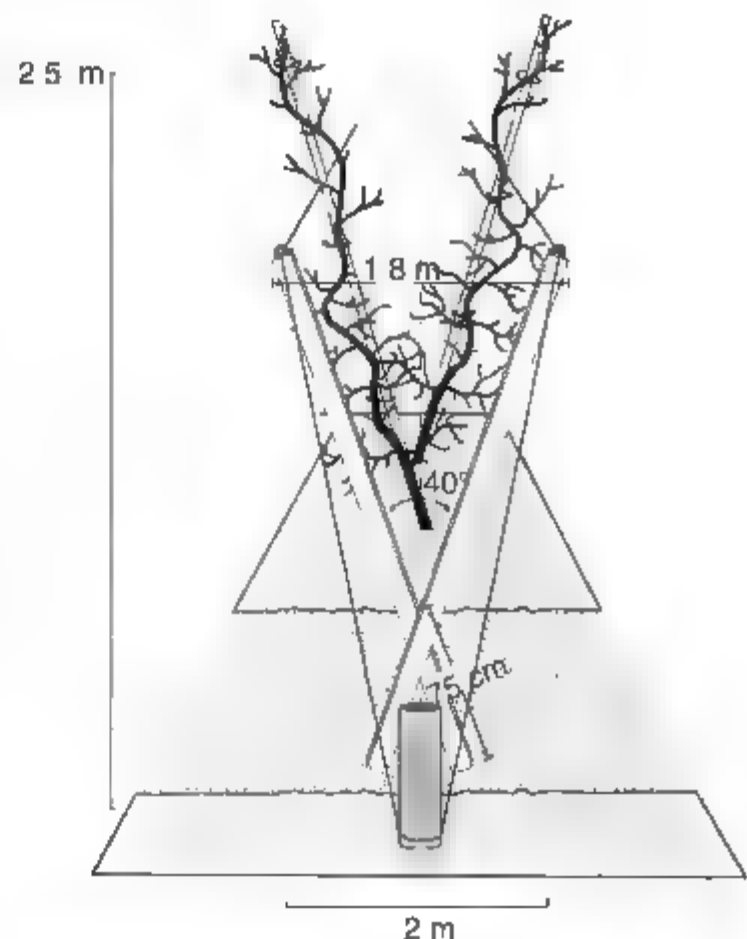


Fig. 15.11. The G ttingen V-slender-spindle tree consists of a slender-spindle-trained tree leaned 20° away from vertical and attached to a support pole. Alternating trees are leaned to opposite sides of the V trellis.

Table 15.9. Pruning and training plan for the V-sender-spindle system. (NB Northern-hemisphere dates.) (Adapted from Robinson and Hoying, 1994.)

First year	
At planting	Plant highly feathered trees. Adjust graft union to 10 cm above soil level. Remove all scaffolds below 60 cm, using a flush cut. Trees with three or more scaffolds (25 cm long) should be headed at uppermost scaffold. The uppermost side-branch should then be tied up as the new leader. Scaffolds longer than 45 cm should be headed by removing one-third their length.
Soon after planting	Install V-shaped-trellis system with an individual angled tree stake at each tree. The support system should allow trees to be supported to 2.5 m. Attach alternating trees to each side of the V-support system by leaning the whole tree to the trellis. Attach tree to support system with permanent ties, leaving a 5 cm diameter loop to allow for trunk growth.
5–10 cm growth	Attach clothes-pegs to new side-shoots on leader to promote wide crotch angles.
July	Tie developing leader to support pole with permanent tie. Remove clothes-pegs.
Second year	
Dormant	Where growth has been good (> 45 cm of terminal growth), tie leader and vigorous scaffold branches horizontal. Alternatively, remove leader down to a horizontal scaffold branch and tie it up as the new leader.
Mid-June	Tie leader back to stake, allowing smoothly curving bends to remain. Hand-thin fruits to 15 cm apart.
August	Tie up lower scaffolds not expected to support the crop.
Third year	
Dormant	Where previous leader bending has significantly weakened the top of the tree, DO NOT PRUNE. Where leader is vigorous, tie leader horizontal or alternatively remove leader down to a suitable horizontal side-branch and tie it up as the new leader. Remove upper branches that extend into the interior of the V.
Mid-June	Tie leader back to stake allowing smoothly curving bends to remain. Tie down vigorous limbs that will not bend with the weight of the crop. Hand-thin fruits to 15 cm apart.
August	Tie up lower scaffolds not expected to support the crop. Alternatively, do not tie up but prune back scaffolds to prevent limb breakage and preserve tree structure. Remove shoots in the interior of the V.
Fourth year	
Dormant	DO NOT PRUNE LEADER. Remove upper branches that extend into the interior of the V. Remove overly vigorous upright limbs that are more than two-thirds the diameter of the leader, using a bevel cut. Tie down other vigorous, upright limbs below the horizontal overlooked during third summer.
Mid-June	Tie leader to stake, allowing smoothly curving bends to remain. Tie up fruitful scaffolds that will not support crop weight.
August	Lightly summer-prune to encourage light penetration and maintain pyramidal tree shape. Remove shoots in the interior of the V. Tie up lower scaffolds not expected to support the crop.
Fifth and sixth year	
Dormant	Limit tree height by cutting leader into 2- or 3-year-old wood back to a horizontal fruiting branch. Remove upper branches that extend into the interior of the V. In each year, remove at least one undesirable bottom-tier scaffold until four remain. Shorten bottom-tier scaffolds by pruning back to side-branch to facilitate equipment movement and preserve fruit quality on lower limbs. Shorten branches that have become pendant back to horizontal portion of the branch.
August	Lightly summer-prune to encourage light penetration and maintain pyramidal tree shape. Remove shoots in the interior of the V.

Table 15.9. *Continued.*

Mature-tree pruning	
Dormant	Limit height by cutting leader back to a fruitful side-branch. Remove upper branches that extend into the interior of the V. Shorten bottom-tier scaffolds by pruning back to side-branch to facilitate equipment movement and preserve fruit quality on lower limbs. Shorten branches that have become pendant back to horizontal portion of the branch. Remove one or two vigorous upper scaffold limbs each year, preserving all weak-fruiting wood and permanent lower-tier scaffolds.
August	Summer-prune to encourage light penetration and maintain pyramidal tree shape. Remove shoots in the interior of the V.

15.5.9 Advantages and disadvantages of V systems

The benefits of V systems have led to a large increase in their popularity over the last 25 years. In some parts of the world, V systems account for a significant portion of new apple plantings. The primary advantage of V systems is that they have very high yields at maturity (Hutton *et al.*, 1987; van den Ende *et al.*, 1987; Robinson and Lakso, 1989; Robinson *et al.*, 1991a; Robinson, 1992a). The high yields have been related to high levels of light interception (Robinson and Lakso, 1991). V systems allow less light to fall on the tractor alleys between rows as a result of the arms of the V-shaped canopy growing over the tractor alleyways. With pyramid-shaped trees, considerable light is lost between rows and similar levels of light interception to V systems are only achieved with multiple-row systems or with very tall trees (Robinson and Lakso, 1989). Yields of V-shaped systems are also higher than those of other systems, primarily due to the higher tree densities utilized by the V systems. Direct comparisons of the V shape with other tree forms at the same tree density have shown that the V systems have consistently yielded more than other vertical systems by 8–15% (Robinson, 1997a).

Growers have observed that another advantage of V systems is that the rectangular planting designs used in V systems, where in-row spacings are much smaller than between row spacings, allow them to be managed with conventional equipment, whereas the bed or very high-density systems require very narrow equipment. In most cases, tractors can drive under part of

the tree canopy with V systems since the canopy grows up over the tractor alleyways. Typical between-row spacings for the Tatura trellis are 6 m, for the Geneva Y trellis 4 m and for the V slender spindle 3.5 m. The ability to use existing equipment in new V-shaped orchards reduces the equipment cost when converting old, low-density orchards to new, modern, high-yielding orchards. From a tree-canopy management and yield perspective, the highly rectangular planting designs of the V systems direct most of the canopy growth across the row over the tractor alleyway, whereas most other systems direct growth both across the row and down the row into the next tree. Research with V systems has shown that cumulative yield over 11 years increased with increasing rectangularity, up to a rectangularity of 4 (between-row spacing four times greater than in-row spacing) (Robinson, 1997b). In contrast, research with conic-shaped trees has shown that square designs are better, since the canopy of a conic-shaped tree extends down the row and across the row in equal distances. With conic-shaped trees, the highest yields are with a rectangularity of 1 (Parry, 1978).

Improved light distribution within the canopy has been another presumed advantage of V-shaped canopies. V-shaped canopies are usually two-dimensional and should have better light exposure than spherical or conic-shaped trees, which are three-dimensional. However, light distribution depends on light transmission through the canopy and, if the canopy is too dense, the underside of the trellis can be heavily shaded (Robinson and Lakso, 1991). In addition, the

underside of the trellis can be heavily shaded if the canopy arms of adjacent rows grow together. Our experience with this system indicates that a minimum of 1.5 m of open space between canopy arms of adjacent rows is necessary for good fruit colour.

Another advantage of V systems, like the planar canopy systems, is that the tree training can be systematized. Training recipes can be developed where limb or branch training can be simplified and performed by unskilled labour. This is aided by the trellis, which serves as a template of tree shape.

Another reported advantage of V systems is reduced fruit sunburn in high-light-intensity climates. Good data showing reduced sunburn are lacking. However, in an unreplicated trial, van den Ende *et al.* (1987) reported lower fruit sunburn on 'Nijisseiki' Asian pears when grown on Tatura trellis than when grown using central-leader, multiple-leader or bush-trained trees. More solid data on sunburn are needed before this advantage can be claimed.

The possibility of mechanical harvesting is another advantage of V systems (Chalmers *et al.*, 1978). Van Heek and Adem (1980) and Gould *et al.* (1986) have reported on mechanical harvesters for Tatura-trellis peaches. Removal averaged 95%, with 5% lost to the ground. Damage was minimal with plums but greater with peaches. Robinson *et al.* (1990) showed that Y-trellis apple canopies had less damage when mechanically harvested with a trunk-impact shaker than central-leader-trained trees. This was primarily the result of placing the catching pads near the fruit, thereby reducing the distance fruits fall and the possibility of contacting other fruits or branches. If hand-harvest labour becomes limiting, the V-shaped canopies offer the best potential for mechanical harvest.

The primary disadvantage of V systems is the high cost of establishment and initial tree training. Trellis costs of V systems are generally more expensive than the costs of conic or vertical planar systems. The cost of an installed trellis for a V system is around US\$6500 ha⁻¹ and, when added to the cost of trees (US\$7500 for 1500 trees ha⁻¹), results in an establishment cost of around US\$14,000 ha⁻¹. This compares with about US\$12,000

for a vertical-axis system at the same density.

A second disadvantage is the greater cost to train the trees over the first 4 years compared with the central-leader or vertical-axis systems. We have estimated that the labour cost for tree training in years 1–4 is about US\$5000 ha⁻¹, compared with US\$3500 ha⁻¹ for the vertical-axis system.

A third possible disadvantage is that fruit size from V systems is smaller than from vertical systems. Robinson *et al.* (1991a) have shown that with 'Empire', fruit size with the Y trellis was smaller than with the central-leader system. However, the Y trellis consistently had heavier crop loads than the central-leader system, which could explain the smaller fruit size. Statistical adjustment of fruit size for crop load showed no significant difference between the systems. Nevertheless, the shape of the V systems leads to high light interception and hence high heat loads at midday, which could lead to greater water stress on the V systems. This could result in smaller fruit size.

Growers who have adopted a V system have generally done so because of the benefit of increased yield or the presumed benefit of improved fruit quality (primarily reduced sunburn and improved red colour). The ultimate value of V systems depends on their economic performance. Although they have higher yields than other systems, they also have higher costs. V systems will probably be better than conic-shaped tree systems under conditions of high sunburn and high winds or where all the fruit must be picked from the ground, since the V systems can intercept more light with short-stature systems than pyramid-shaped systems.

15.6 Tree-support Systems

Tree-support systems were originally designed to prevent tree leaning with poorly anchored rootstocks, such as M.9 and M.26. However, modern pruning and training schemes, combined with dwarfing rootstocks, favour the production of fruit before the tree's own canopy can support the crop. Thus modern tree-support systems are designed to support much of the weight of

the crop to prevent the branches of the tree from breaking. The preservation of the tree canopy during the early years often depends on the engineering of a support system. A good support system for a high-density orchard must be viewed as an investment that allows fruit production in the early years while preserving the tree canopy for future, large, mature yields. In reality, the support system of a modern orchard is an investment that provides large returns rather than being just an expense. Where trees are properly supported, larger trees can be grown in the first 5 years, resulting in larger crops each year. Without a proper support system, trees must be pruned more heavily to stiffen the wood to support the crop. This results in smaller trees and smaller crops.

Trees can be supported either by individual tree stakes or by a trellis. Historically, the conic-shaped canopy systems were supported with individual tree stakes, while the planar and V-shaped canopy systems were supported by a trellis. Currently, the choice of tree-support method is often an economic decision. Many growers prefer the use of individual tree stakes over a trellis, since it allows workers to move around the tree during harvest. With low and moderate tree densities, it is often economic to provide individual tree supports. However, with very high tree densities, it becomes uneconomic to use individual tree stakes and a trellis must be used. In northern Europe, where high-density orchard systems were first

developed and were based on short-stature trees, the most common tree support was a 2.5 m long, round wooden pole placed at each tree. In southern Europe and North America, where taller trees were common, trellises were the norm and utilized larger-diameter 3.5 m long wooden poles to support three to six wires. As growers have tended towards higher and higher densities, the most common support system in the world today is a hybrid trellis with inexpensive individual tree stakes (Fig. 15.12). This system has a strong anchor system at each end of the row, with wooden support poles spaced at 15 m along the row. A single wire is strung along the tops of the poles and tightened to a high tension. At each tree, an inexpensive individual tree stake is installed and tied to the trellis wire. Individual tree stakes have been made from wood, bamboo, galvanized steel conduit pipe or recycled angle iron. The tree is trained up the support pole until it reaches the wire, when it is tied to the wire. This system provides the lower-cost benefits of a trellis and the management flexibility of an individual tree stake.

The materials used for tree support around the world depend on the materials available in that region and the growers' ingenuity. Growers in western North America, northern Europe and New Zealand have had ready access to inexpensive chemically treated wooden posts that do not rot. Such posts are not as readily available in other regions at the same cost. In some locations,

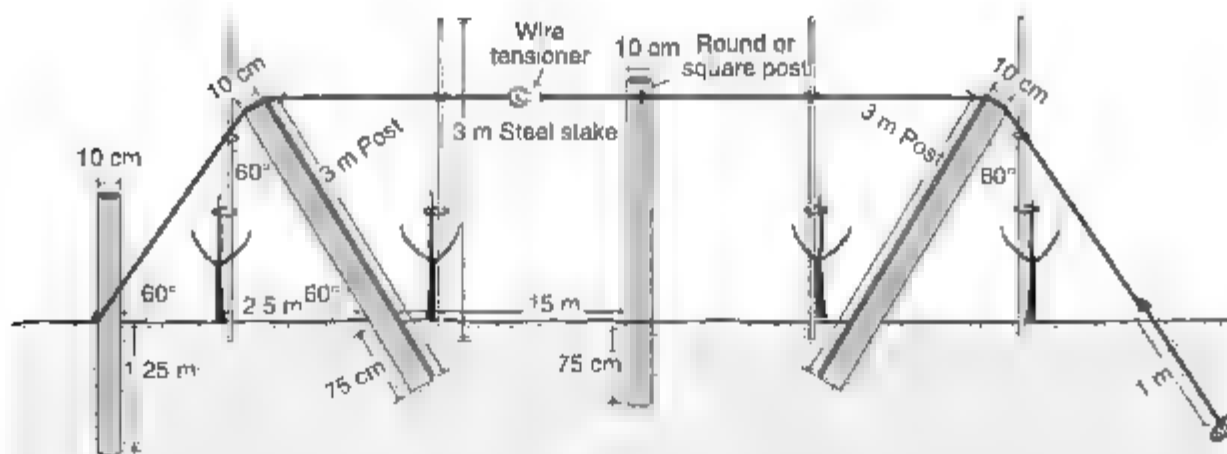


Fig. 15.12. The hybrid trellis with tree-stake support system for both conic and V-shaped canopy systems with either bamboo or steel-pipe tree stakes.

untreated black locust poles are commonly substituted, with equal results. In areas of the world where wood is not available or is prohibitively expensive, growers have been successful using reinforced-concrete posts.

Trees on dwarfing rootstocks, such as M.9, must be supported to the desired height of the mature canopy. With the slender-spindle system or the Penn State thin-wall trellis, the support system only needs to be 2 m high since the systems are based on all work being done from the ground. However, with the taller systems, such as vertical axis, slender pyramid or HYTEC, the trees must be supported to 3 m high. In areas where long poles are inexpensive, it is common to use 3.6 m tall poles, with the top of the pole and the top wire at 3 m above the ground. In eastern North America, 3.6 m wooden poles are almost double the price of 3 m long poles, so a less expensive alternative, which still provides support up to 3 m, is to use the shorter 3 m poles with the top of the pole and the top wire at 2.4 m above the ground. At each tree a 12 mm diameter, 3 m long galvanized-steel pipe is used as an individual tree stake. The steel pole is inserted in the ground only 15 cm, thus providing a rigid support for the tree above the wire (Fig. 15.12).

Support systems vary widely in cost (Table 15.10). The least expensive high-density support systems are the vertical three-to five-wire trellises, while the most expensive systems are the slender spindle and the elaborate trellis systems, such as the V slender spindle, Tatura, Ebro or Lincoln. The relatively greater cost of using individual wooden poles for tree support with the slender-spindle system has prompted many slender-spindle growers to switch to a three-wire trellis or a hybrid single-wire trellis, with either a steel-pipe or a bamboo tree stake for a support system. The super-spindle system, which is the highest-density apple system, utilizes a simple trellis and thus has one of the least expensive support systems per hectare, but the very high tree densities make it the most expensive orchard system to plant.

15.7 Field Comparisons of Orchard Planting Systems

A number of field comparisons of planting systems have been conducted in the last 30 years. In most cases, the trials have compared complete systems (unique combinations of tree density, tree form, rootstock and

Table 15.10. Support-system costs for high-density orchard systems.

System	Tree density (trees ha ⁻¹)	Support-system description	Material costs (US\$ ha ⁻¹)	Labour costs (US\$ ha ⁻¹)	Total cost (US\$ ha ⁻¹)
Central leader	500	Temporary wood trunk stake (2 m × 5 cm)	998	349	1348
Mini-central leader	850	Steel-pole tree stake (3 m × 5 cm)	1470	336	1806
Free palmette	950	Five-wire trellis (3 m high)	2396	1937	4333
Penn State trellis	1100	Three-wire trellis (2 m high)	2497	1559	4056
Vertical axis, slender pyramid or HYTEC	1500	Hybrid trellis (single-wire trellis 2.5 m high with 3 m steel-pole tree stakes)	3252	1604	4856
Vertical axis, slender pyramid or HYTEC	1500	Hybrid trellis (single-wire trellis 2.5 m high with 3 m bamboo-pole tree stakes)	2499	1604	4103
Geneva Y trellis	1500	Y trellis (2.2 m high) with three wires per side	3025	2653	5678
Slender spindle	2000	Wooden tree stake (2.5 m × 5 cm)	5202	4161	9363
V slender spindle	3000	V trellis (2.2 m high) with one wire per side and with 3 m steel-pole tree stakes	5549	3053	8603
Super-spindle	5000	Three-wire trellis (2.4 m high)	2049	1721	3770

training system), which have made it difficult to determine the individual effects of tree density, training system or rootstock. Almost all field comparisons of systems have shown that the higher-tree-density systems have had higher yields than lower-density systems, at least in the early years.

Ferree (1980) studied four systems: slender-spindle/M.9, palmette trellis/M.9, mini-central leader/interstem and large central leader/MM.106. He found that cumulative yield was related to planting density, with the slender spindle having the highest yield. However, the soils and climate in Ohio gave relatively high vigour, which resulted in poorer light levels within the canopy of the slender-spindle trees than the palmette or mini-central leader. The latter two systems had more open canopies and greater crop loads. The palmette system had the highest yield efficiency, indicating the best balance between vegetative growth and cropping.

Blizzard *et al.* (1988) compared slender spindle/M.9, palmette trellis/M.9, Lincoln canopy/M.26 and central leader/MM.111. The slender-spindle system, with a density of 4000 trees ha⁻¹, had the highest yield and the central leader, with a density of 270 trees ha⁻¹, had the lowest yield. The palmette and the Lincoln canopy were similar in yield and had the same density. At maturity, the palmette system had the most open canopy and the best fruit quality, while the Lincoln canopy and the slender spindle had the poorest fruit quality (Ferree *et al.*, 1989). The latter two systems had more dense canopies and poorer light exposure to the lower part of the canopy. In this study, the tree vigour of the soil and climate gave too much growth for the high-density slender-spindle system and, despite high yields, gave poor fruit quality.

Robinson and Lakso (1989) compared four orchard systems (slender spindle/M.9 at 1960 trees ha⁻¹, Y trellis/M.26 at 1283 trees ha⁻¹, mini-central leader/M.9/MM.111 at 961 trees ha⁻¹ and large central leader/M.7 at 450 trees ha⁻¹) in one of the few trials to be conducted for longer than 20 years. Yields during the early years were highest for the slender spindle, followed by the Y trellis and mini-central leader, and lowest for the large

central-leader system. Yields per hectare were largely a function of the planting density. As the orchard matured, the Y trellis had the greatest yield, while the yields of the three conic-shaped systems continued to be a function of tree density. This anomaly was due to the greater light interception at maturity of the Y-trellis system than that of any of the other systems. This same yield ranking among the four systems continued until the end of the trial at age 22 (Robinson, 2000b). In the early years, there were few differences in colour, but the high-yielding systems had slightly smaller fruit size than the low-yielding systems, due to heavier crop loads. In the second decade of the orchard's life, the mini-central leader had the best colour, followed by the large central-leader and slender-spindle systems. The Y trellis had poorer colour in years 11 and 12 as the tops of adjacent rows grew together. After corrective pruning and the application of renewal-pruning strategies to that system, fruit colour was similar to that of the other systems. Fruit size tended to be smaller with the Y trellis than with other systems. It appeared that this was largely due to heavier crop loads, however, there also appeared to be a consistent but small effect of system on fruit size. It may be that the high interception of light during the midday hours results in larger heat loads and water stress on the Y-trellis canopy than on the conic-shaped trees.

Lespinasse *et al.* (1992) compared seven systems (vertical axis, structured axis, Tatura, pergola, palmette, MIA 15°, MIA 30°) on 'Royal Gala' trees grafted on M.26. Results showed that the best cumulative yield and fruit size were obtained with the four training systems vertical axis, structured axis, Tatura and palmette. The vertical-axis system was characterized by the best fruit colour, indicating that this system optimized light distribution within the tree canopy.

In a comparison of slender spindle and super spindle, Weber (2000) has shown greater cumulative yield with the super spindle compared with the slender spindle, but reduced fruit size and fruit colour. Wagenmakers *et al.* (1994) also showed that, although total production increased with higher tree densities, the proportion of well-

coloured fruit decreased sharply when tree density exceeded 10,000 trees ha⁻¹. In addition, the very close spacings utilized in the super-spindle system have resulted in greater growth in the upper part of the tree compared with the lower part of the tree, thus increasing the risk of losing production in the lower canopy zones, due to light deficiency and less vegetative growth at the bottom part of the tree (Weber, 2000). Thus orchard light management with the super spindle is very important to ensure productivity (Wagenmakers, 1995).

Orchard trials with V-shaped canopies have shown them to be highly productive and highly efficient at converting light energy into fruit. Among four systems, the Geneva Y trellis/M.26 had the highest conversion efficiency (6.5 g fruit MJ⁻¹ photosynthetically active radiation (PAR)), followed in order by the slender-spindle/M.9, interstem and central-leader/M.7 systems (4.0 g fruit MJ⁻¹ PAR) (Robinson and Lakso, 1991). The greater efficiency of V systems is probably due to the good exposure of the fruiting spurs in the Y-trellis system.

Widmer and Krebs (2001) compared slender-spindle, V slender-spindle, Drilling and Mikado systems at several densities. With increasing tree density, yield per tree decreased, but yield per hectare increased. However, the increase in yield per hectare was proportional to the increase in trees per hectare. At the highest tree density, fruit size was reduced. The open-tree forms of the Drilling and Mikado systems had lower yield in the early years, but similar yield and better fruit quality when the trees were mature.

To separate the effect of planting density from training system, Robinson (1997a) compared four training systems (slender spindle, vertical axis, Y trellis and horizontal palmette), each at two tree densities, using two cultivars with distinct growth habits ('Jonagold' and 'Delicious'), but all on the same rootstock (Mark). Over the first 8 years, the higher-density version of each system produced more than the low-density version. However, despite the very different training strategies imposed on the trees over the first 5 years there was no significant difference in third-year yield among the systems. In the

fourth eighth years, the Y trellis had slightly higher yields than the other systems, but the differences were not large. After 8 years, the Y trellis had the greatest cumulative yield (8–15% more), while there were no significant differences among the other three systems. These results indicate that any one of the modern training systems will produce excellent results if planted at the same density and on the same rootstock.

Buler *et al.* (2001) compared the slender-spindle, HYTEC, Solen and Mikado systems in Poland. They found that the slender-spindle and Mikado systems had higher yield than the HYTEC or Solen systems. The Mikado system gave the best fruit size and light distribution in the canopy

15.8 Underlying Principles of High-density Orchard Planting Systems

Although modern orchard planting systems vary in specific tree-training recipes, they are based on many of the same underlying principles (Palmer and Warrington, 2000). These include high tree density, precocious and dwarfing rootstocks, high light interception at maturity, good light distribution within the canopy and a balance between vegetative growth and cropping.

15.8.1 Tree density

Tree density is the single most important factor affecting early yields of any orchard system. In the early years of an orchard's life, light interception by the canopy is low, which limits yield potential. A major objective during the first few years is to develop the canopy as quickly as possible so that full canopy closure can be achieved. With tree densities below 500 trees ha⁻¹ this can take 7–12 years. With densities between 1500 and 3000 trees ha⁻¹, which are the most common densities in modern high-density orchards around the world, tree-canopy closure can be achieved by the end of the third or fourth season. With the very high tree densities of the super-spindle system (> 4000), canopy closure can be achieved by the end of the first year

Data from several studies show that, during the early years, yields are related to tree density, with the highest tree density producing the highest cumulative yield (Fig. 15.13). The relationship of tree density and cumulative yield is linear in the first 2–3 years, but by year 6 the relationship is curvilinear (Fig. 15.13). Data from New York also show a curvilinear relationship over the first 11 years of an orchard's life (Fig. 15.14). At the lower end of the density continuum, the relationship is almost linear, with a slope of 150 kg per tree indicating that as tree density

is increased an additional cumulative yield of 150 kg ha⁻¹ was obtained for each additional tree per hectare. This would be about eight times the cost of the additional tree. At the higher tree densities, the gain in cumulative yield was very small, with a slope of 70 kg per tree for 'Jonagold' and 20 kg for 'Empire'. This would be about 3.5 and 1 times the cost of the additional tree for 'Jonagold' and 'Empire', respectively. In northern Italy, a comparison between a super-spindle orchard with 6143 trees ha⁻¹ and a string-tree orchard with 13,134 trees

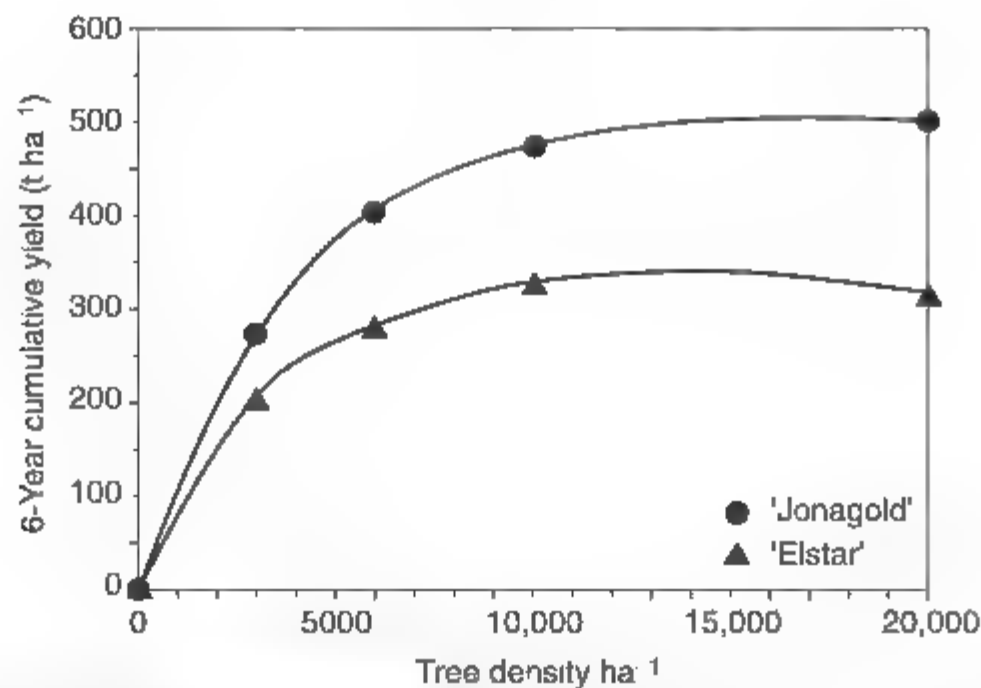


Fig. 15.13. Relationship of tree density and cumulative yield over the first 6 years of an apple orchard in The Netherlands (from Bakhoven-Baart *et al.*, 2000)

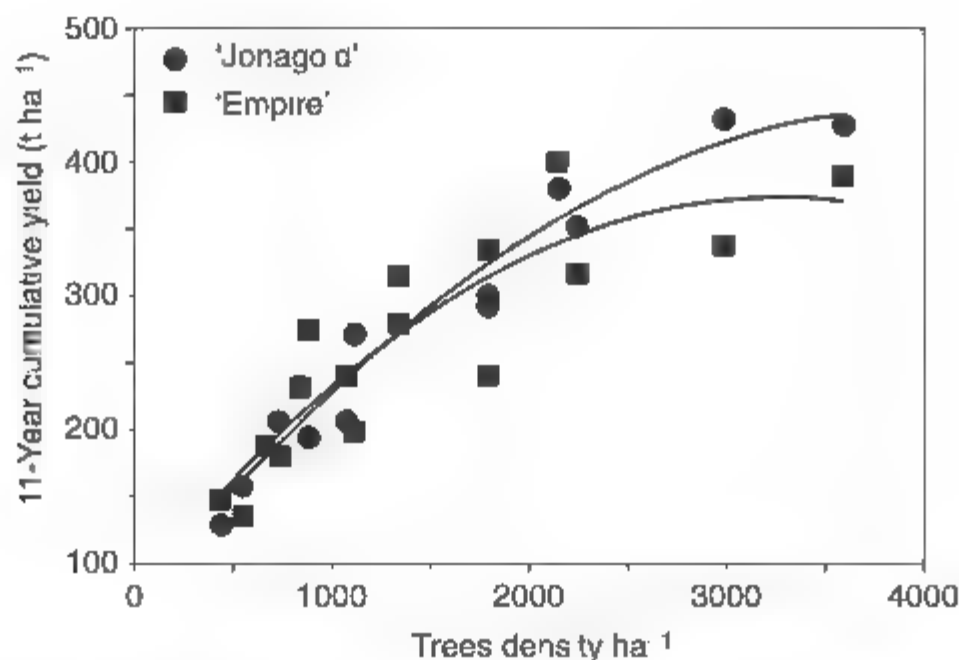


Fig. 15.14. Relationship of tree density and cumulative yield over the first 11 years of an apple orchard on M.26 trained to Y-trellis system in New York State, USA ('Jonagold' $r^2 = 0.95$; 'Empire' $r^2 = 0.79$).

ha⁻¹ showed that, with a twofold increase of tree density, only a 1.17-fold increase in yield in year 2 was obtained and only a 1.09-fold increase in yield in year 4 with 'Golden Delicious' (Österreicher, 1993). The relationship of planting density and cumulative yield over the life of an orchard is typical of the law of diminishing returns, which states that additional increases in an input factor (tree density) produces a smaller and smaller increase in an output factor (yield). At the high end of this curvilinear relationship, additional increases in tree density will not produce enough extra yield to pay for the additional costs incurred to purchase and plant the extra trees (Weber, 2001; Widmer and Krebs, 2001).

The optimum tree density in any apple-producing area is an economic question. The laws of economics dictate that the optimum density will be less than the density with the highest yield. In Europe, average planting densities increased up to about 1995 to 5500–6000 trees ha⁻¹, but in the last 6 years there has been a trend towards more moderate planting densities, ranging between 2800 and 3800 trees ha⁻¹ (Weber, 2000). The reason why more moderate planting densities are favoured may be explained by rising tree prices and lower returns for the fruit. It has become more difficult to justify the high investment cost of the super-spindle system. Another reason for more moderate plant densities is the difficulty of managing excessive vigour, especially of virus-free plant material of new cultivars, such as 'Gala' and 'Braeburn' (Weber, 2000, 2001). Many growers have not been successful in balancing the vegetative and reproductive growth of a super-spindle orchard. Our latest economic analyses under New York conditions have indicated that densities between 1000 and 2500 trees ha⁻¹ are more profitable than lower or higher densities. The results of our economic analysis may not be valid for other parts of the world, with different fruit, tree and land prices. Nevertheless, for most fruit-growing areas of the world, it is our opinion that tree densities up to about 2500 trees ha⁻¹ will result in greater profitability and moderate levels of risk. Above this density, it appears that, despite producing greater

cumulative yields, profitability is only slightly greater and, in some cases, less than with lower densities; moreover, the economic risk is increased significantly with very high-density orchards. It should be noted, however, that the relationship of tree density and early cumulative yield can be modified by a number of factors, including initial tree quality and pruning severity, which would change the optimum economic density.

Tree density, when properly calculated, considers the vigour of the cultivar, the vigour of the rootstock and soil strength. With vigorous scion cultivars, growers should use a more dwarfing stock and greater planting distances. With weak scion cultivars, a more vigorous rootstock should be used and/or closer planting distances. Despite some latitude in planting distances, growers should remember that, to obtain high early yields, high tree densities are essential. Thus in almost all cases, planting distances should not exceed 2.5 m in the row or 4.5 m between rows.

15.8.2 Rootstock

Although high tree density is the single most important factor affecting yield in the early years of an orchard's life, dwarfing rootstocks are the foundation for any successful high-density planting system. The choice of rootstock in combination with the choice of scion cultivar defines the typical tree vigour and final tree size, which dictate its planting density. Rootstock has a dominant effect on tree precocity (flowering and cropping in the early years) and productivity. In many ways, the choice of rootstock determines the potential yield of a given cultivar and ultimate profitability. The rootstock also determines tree size, which determines a system's labour efficiency. Other rootstock characteristics important to consider in selecting the right rootstock include tolerance to diseases, such as fire blight, *Phytophthora* and crown gall, tolerance to insects, such as woolly apple aphid (WAA), and tolerance to abiotic stresses, such as drought and/or water tolerance, and spring-frost and winter-cold tolerance. Rootstock can also have a direct effect on fruit size.

Most successful high-density plantings are planted with dwarfing rootstocks, such as M.9, M.26, B.9, G.16, CG.202 or O.3, or with interstem trees of M.9 and MM.111 or MM.106. Although it is possible to plant high-density orchards on semi-dwarf rootstocks, such as M.7 or G.30, or some semi-vigorous rootstocks, such as MM.111, MM.106 or M.793, their lack of precocity is a serious limitation to this approach. In addition, their inherent vigour makes management of the mature high-density orchard much more difficult. Dwarfing rootstocks limit tree vegetative growth when trees are mature, which results in less winter and summer pruning.

Within the M.9 family of dwarfing rootstocks, there are significant differences in vigour between clones. The weaker clones (M.9 NAKBT337 and M.9 Fluere56) are especially useful with vigorous scion cultivars on virgin soil. The more vigorous clones (M.9 Pajam 2, M.9 Nic29, M.9 EMLA) are much better when orchards are planted on replanted soil or when weak scion cultivars are used. Although M.9 and M.26 are used around the world with great success in high-density plantings, they are both susceptible to fire blight and WAA. In addition, M.26 is very susceptible to *Phytophthora* root rot. The new dwarfing rootstocks that are resistant to these problems, such as the Cornell Geneva series, should improve the worldwide performance of high-density orchards.

15.8.3 High light interception at orchard maturity

Mature yields of all apple orchards, regardless of planting density or pruning system, are related to total light interception (Palmer, 1989, 1997; Barritt *et al.*, 1991; Robinson and Lakso, 1991; Wagenmakers, 1991; Robinson, 1992b; Robinson *et al.*, 1993). The theory of light interception has been reviewed several times (Cain, 1972; Jackson and Palmer, 1972; Jackson, 1980, 1985; Sansavini, 1982). Although early yields appear to be largely a function of tree density and rootstock and not greatly influenced by training system, mature yields can differ substantially depend-

ing on light interception. Light interception is largely a function of tree shape and arrangement.

Mathematical models of light interception have been constructed to estimate light interception from different canopy shapes and planting configurations (Jackson, 1981, Palmer, 1981). From this body of work, a few main points are important for this discussion. Orchard canopies, unlike those of other crops, are of necessity discontinuous, due to the alleyways maintained between rows for orchard machinery, which results in a large proportion of the land area not being covered by trees (Jackson, 1980). This results in low values for leaf area index (LAI) and total light interception for orchard canopies when compared with other crops. In addition, leaf area is not randomly distributed over the land area, as in annual crops, but is clumped in trees, branches and spurs. Light interception is low when the orchard is planted and increases as the orchard develops in relation to total LAI. Light interception in orchards can be raised by: (i) increasing the density of foliage in the canopy; (ii) increasing the height of the trees relative to the clear-alley width; or (iii) increasing the number of trees per hectare (Corelli and Sansavini, 1989). Because of the tractor alleys used for orchard management, light interception is more strongly influenced by tree numbers per hectare and ratios of tree height to clear alleys than by canopy density.

Cain (1970) introduced the idea that orchard light interception should be considered over the lifetime of the orchard. He found that the mean lifetime fraction of land covered by tree canopy increased as tree size decreased and tree planting density increased. A meaningful variable of orchard performance would be mean lifetime fraction of light intercepted, but few studies have calculated such an index.

Jackson (1970) has shown that the widely spaced bush trees common in many older orchards, which are large at maturity, intercept very little light when they are young and yet when full-sized they have excessive within-tree shading and relatively low LAIs. The realization that significant land and light

resources were wasted in the early life of an orchard has encouraged the planting of higher and higher tree densities. This has resulted in greater early yield and greater lifetime light interception. Verheij and Werwer (1973) examined light interception in low- and high-density hedgerows of 'Golden Delicious'. The low-density plots (1100 trees ha^{-1} on M.9 and 660 trees ha^{-1} on M.2) intercepted roughly half of the incident light at maturity, and yields peaked at 40 t ha^{-1} . The high-density plots (3300 trees ha^{-1} on M.9 and 2260 trees ha^{-1} on M.2) intercepted 66% and 75% of available light, respectively. Yields were more than 70 t ha^{-1} in their sixth and seventh years, but thereafter yields declined due to inter-tree competition. In a spacing trial, Palmer and Jackson (1974) have reported that, with densities ranging from 853 to 3746 trees ha^{-1} , yield and light interception were approximately linearly related. Light interception was closely related to LAI, not just trees per hectare.

Trees can be arranged as single rows, as multiple rows, as a bed system with occasional drive alleys or as meadow arrangements that have no drive alleys. The goal of each arrangement is to maximize the interception of sunlight. Wertheim *et al.* (1986) examined light interception of high-density single-row, three- and six-row bed and full-field systems. They found that light interception was positively related to tree density and to yield. The effect of the tree arrangement was less important than tree numbers per hectare for increasing total light interception and yield. The results of tree arrangement showed that a single-row or full-field arrangement of trees gave better yields than the three-row system at equivalent tree densities. Increasing tree planting density has been the most important means of increasing the early yield and early light interception of young orchards. Barritt (1989) found that tree density was more important than training system or rootstock for improving light interception and yield in the third year with 'Granny Smith' apple trees.

Palmer and Jackson (1977) developed a bed system to achieve high light interception with a more even distribution of foliage over the orchard floor. The bed system had trees

spaced 1.5 m by 0.5 m in a 14-row bed separated by tractor alleyways. It achieved ceiling levels of LAI and light interception 2 years after planting. Interception was comparable with that of a closely planted hedgerow system (2.9 m by 0.9 m) and yet the bed system had a much lower LAI, due to a more even distribution of foliage over the orchard floor. They concluded that LAI was the largest single factor influencing light interception in discontinuous orchard canopies; however, the LAI/light interception relationship could be modified to some extent by leaf-distribution pattern over the ground area. More recently, Palmer (1988) has shown that bed systems can intercept up to 80% of PAR from the end of June until October and yield 78 t ha^{-1} in the third year. The more complicated tree arrangements of multi-rows and bed systems have been more difficult to manage than single rows. Intensive bed systems (Palmer and Jackson, 1977) or multi-row systems (Wertheim *et al.*, 1986) are not compatible with conventional orchard machinery and have generally not yet been adopted widely. Single-row arrangements continue to be the most successful.

Few studies of light interception have been done with planar canopies. Palmer and Jackson (1977) reported that trees on semi-dwarfing rootstocks, trained to tall narrow hedgerows separated by wide alleys, achieved high light interception at maturity, but the between-row shading resulted in poor illumination of the lower portion of the hedgerow, which became unproductive. Shorter hedges on more dwarfing stocks inevitably have lower light interception if the alley width is maintained the same. Such short, vertical, trellised hedgerows are common in New York but, in many cases, tractor alley widths have remained too wide for optimum light interception and yields have been lower than expected. The recent introduction of narrow orchard tractors to the USA should help in reducing tractor alleys.

Robinson and Lakso (1989) studied light interception and yield among three conic-shaped systems and a V-shaped system. Light interception was highest with the Y trellis – 70% of available PAR – compared with 55% for the slender-spindle system,

despite a higher tree density with the slender-spindle system. The increased light interception was the result of the canopy architecture, which allowed the tree canopy to grow over the tractor alleys. There was a linear relationship between yield and tree density over the first 10 years of the orchard life for the three conic-shaped systems, but the Y-trellis system had greater yield than was predicted for its tree density. The increased light interception accounted for a large portion of the increased yield. The Y-trellis, because of its unique geometric shape, had interception levels similar to those of the bed systems of Palmer (1988) or the multiple rows of Wertheim *et al.* (1986) and yet could be maintained with conventional equipment. The light-interception properties of other planar-canopy tree forms have not been studied.

From the mid-1970s to the late 1980s, there was a strong move toward small trees that allowed all orchard management operations to be done from the ground. In many cases, the decrease in tree size has not been accompanied by a reduction in tractor alley width and tree height was kept too low for high light interception. As a consequence, many dwarf orchards have relatively low mature yields. Robinson and Lakso (1989) found that a Y-trellis system intercepted about 70% of available PAR at maturity, while the slender-spindle system intercepted only 55% of PAR, in spite of 30% greater tree density with this system. This illustrates the problem of short-stature trees planted in single rows, where mature light interception is relatively low due to a low ratio of tree height to clear alleys. There is a relationship between tree height, row spacing and light interception. Greater tree height at the same row spacing increases light interception and, therefore yield, if light distribution to all parts of the canopy is adequate (Jackson, 1980; Barritt *et al.*, 1991; Robinson and Lakso, 1991; Robinson *et al.*, 1991b; Wagenmakers and Callesen, 1995). For optimum light interception, the ratio of tree height to row spacing should be 0.8–0.9. Many of the problem orchards in the 1980s, which had short trees and utilized existing wide machinery, had height-to-row spacing ratios of 0.5 or less. Using the optimum ratio, typical row

spacings used in high-density orchards of 3.5–4.5 m should have mature tree heights of 2.8–4.0 m. Failures of mature high-density orchards to produce expected yields at maturity can usually be traced to trees not intercepting enough light. Where growers desire short-stature trees (< 2.5 m tall) that can be picked from the ground, they should reduce tractor alleys to 2 m or less.

15.8.4 Good light distribution within the mature canopy

As trees mature, the challenge becomes to utilize canopy-management strategies that maintain good light distribution within the canopy. With all apple-planting systems, there is a natural progression towards an umbrella-shaped tree, where the upper limbs receive more light intensity and thus grow more than the lower limbs, causing shading of the lower branches. Shaded areas of the canopy produce smaller fruit size, poorer fruit colour, less return bloom and weak fruiting spurs (Jackson, 1970; Jackson *et al.*, 1977; Robinson *et al.*, 1983; Barritt *et al.*, 1987; Lasko *et al.*, 1989b; Palmer, 1989; Warrington *et al.*, 1996; Wunsche *et al.*, 1996). Our work with orchard systems has shown that there are no important differences in fruit quality in the first few years of an orchard's life. However, as the orchards reach maturity, significant differences in fruit colour, size and quality become apparent.

Two approaches have been used to improve the light distribution in mature apple canopies. One is to provide and manage many small openings between branches, which allow light penetration to the centre and lower portions of the canopy. This approach is used with natural tree forms, such as in the central-leader, slender-spindle, vertical-axis, slender-pyramid or HYTEC systems (Wertheim, 1968; McKenzie, 1972; Heinicke, 1975; Lespinasse and Delort, 1986; Barritt, 2000; Tustin, 2000). This approach can be successful, but generally requires a high degree of horticultural skill to manage the growth of the canopy. A second approach is to provide fewer, large, permanent openings for light penetration into canopies

restricted into geometric forms, such as palmette hedgerows, tree walls and A, V or T forms (Chalmers and van den Ende, 1975; Luckwill, 1978; McKenzie *et al.*, 1978; Rosati, 1978; Tukey, 1978; Dunn and Stolp, 1987; Hutton *et al.*, 1987; van den Ende *et al.*, 1987; Palmer, 1988; Lakso *et al.*, 1989a; Correlli-Grappadelli, 2000). This approach generally requires severe geometric restriction of the canopy, expensive support structures and significant labour to place and maintain the branches in specific locations. The value of these different tree forms lies in their light-distribution properties and the attendant improvements in fruit yields and/or quality.

The work of Heinicke (1963) and Looney (1968) showed that large, round-crown trees have a large central core of the canopy that receives very low light intensities (6–30% of full sunlight). The exterior quarter of the canopy had a small percentage of the total leaf area and yet had a large shading effect on the rest of the tree, where the major portion of the leaf surface was located (Fig. 15.15). Heinicke (1963) proposed that 30% of full sun serve as a lower limit of desired light level in apple canopies. Jackson (1970) found a more rapid decline in light level with depth of canopy, with light levels reduced to 34% of full sun within 1 m of the canopy exterior. He found that the main cropping zone of the tree received a minimum of 35% full sun, while the more shaded areas produced relatively few fruits. This result has led to the rule of thumb that the effective

penetration depth of light into unrestricted apple canopies is about 1 m.

Dense hedgerow trees were studied by Verheij and Werwer (1973), who found that average light levels exceeding 50% of full sunlight occurred only at the top periphery of the canopy. Moving down and inward in the canopy, average light levels dropped sharply to about 15% of full sunlight or less. The light penetration into large and small hedgerow trees was similar, but the cross-section of small trees allowed for better light illumination of the interior portions of the canopy (Verheij and Werwer, 1973). Heinicke (1964) also found that, as tree size decreased, the heavily shaded area within the tree decreased. Leaf area per tree decreased with smaller tree size, but leaf area per hectare increased. Dwarf trees with some overlap of canopies had one-third more leaf area per hectare that received > 30% full sun than did standard trees. This indicates a distinct advantage in photosynthetic potential for smaller trees. Forshey and McKee (1970) reported that a large and small tree had the same total dry-matter accumulation per unit of occupied land, despite the lower LAI on the smaller tree. The small tree had a more efficient leaf surface and produced 80% more fruit per unit of occupied land than the big tree. Cain (1970) showed a negative linear relationship between production per unit of tree area and the size of the tree. The relationship showed a decrease of 0.6 kg m⁻² for each metre increase in tree spread. The decreased efficiency of large trees is probably the result of greater internal shading.

Robinson *et al.* (1991b) characterized the light climate of mature central-leader 'Empire'/M.7 and mini-central-leader 'Empire'/M.9/MM.111 trees (interstems), slender-spindle/M.9 trees and Y-trellis M.26 trees at four times during the growing season to examine the effect of tree size, shape and summer pruning on light exposure in the lower part of the canopy. They categorized the canopy into three light zones: (i) well-exposed zone where light levels exceeded 50% full sun; (ii) marginally exposed zone with light levels between 30 and 50% full sun; and (iii) a poorly exposed zone with light levels lower than 30% full

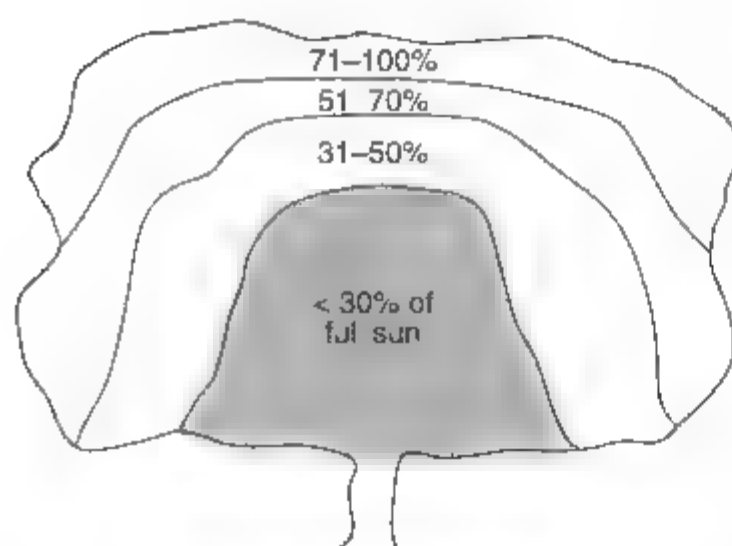


Fig. 15.15. Light distribution in a large round-crowned 'Delicious' apple tree (from Looney, 1968).

sun. At 14 days after full bloom (DAFB) most of the lower interior portion of the central-leader/M.7 trees, which had three tiers of permanent branches, already had poor light exposure (< 30% full sun), while the smaller central-leader/M.9/MM.111 trees, which had two tiers of permanent branches, only had a

very small portion of the canopy with poor exposure (Fig. 15.16). At 44 DAFB, the area of poorly illuminated and marginally exposed canopy areas had increased in both tree types, but a higher proportion of the inter-stem canopy was well exposed. At 74 DAFB, the relative areas of poorly and marginally

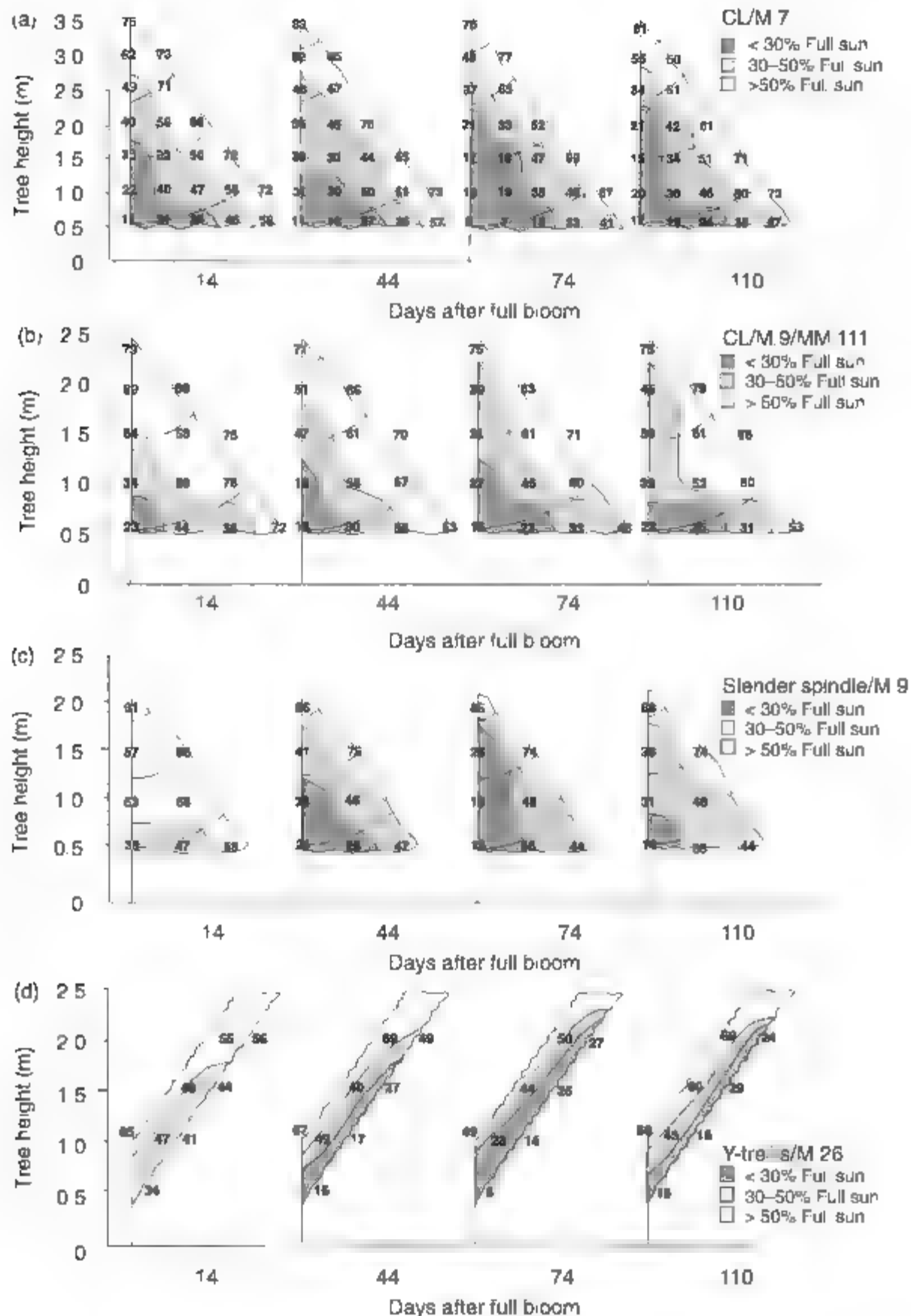


Fig. 15.16. Light distribution pattern at four times during the growing season for 11-year-old 'Empire' trees trained to: (a) the central-leader (CL) system on M.7, (b) the mini-CL system on M.9/MM.111 interstem; (c), the slender-spindle system on M.9; or (d) the Geneva Y-trellis system on M.26 (from Robinson *et al.*, 1991b)

illuminated areas were smaller in the interstem tree than in the M.7 trees; however, both tree types had large areas of poorly illuminated canopy areas. At 100 DAFB, the trees were summer-pruned by removing upright shoots in both the first and the second tiers. Summer pruning improved light distribution in the middle section of the canopy for both tree types. The area of poorly exposed canopy in the interstem tree was reduced to a small area near the trunk on the bottom tier of branches. With the larger M.7 trees, the area of low light level was larger and the area of marginally exposed canopy was not reduced as much by summer pruning. There was very little fruit in the lower interior part of the M.7 trees, while the interstem trees had fruit in all parts of the canopy. Although summer pruning improved the light distribution of the M.7 canopy, it was too late in the season to have much of an effect on fruit-bud differentiation. The improved light distribution of the small central-leader tree resulted from the smaller height and depth of the canopy than in the larger central-leader trees. Barritt *et al.* (1991) have also reported that there is a rapid decline in light exposure to less than 20% full sun by early June for the interior parts of the traditional central-leader canopy. The rapid seasonal decline in light exposure of the interior of central-leader trees has led to modifications of the central-leader tree form, such as the palmette leader (Lakso *et al.*, 1989a), and to summer pruning to improve the light distribution and fruit colour of most red cultivars.

In the study described above (Robinson *et al.*, 1991b), the slender-spindle/M.9 trees had very good light exposure to most of the canopy at 14 DAFB (Fig. 15.16). All parts of the canopy had >30% full sun and only a small portion in the bottom was below 50% full sun. However, by 44 DAFB, light-exposure levels in all parts of the canopy except the top of the tree had dropped considerably, indicating that the gaps between limbs had been closed by new shoot growth. By 74 DAFB, there was a large poorly illuminated area of the canopy, which was markedly reduced by summer pruning, but the marginally illuminated area remained

much the same and only the top of the tree was well exposed. With summer pruning, only upright shoots were removed, but in the compact tree of the slender spindle the spur- and bourse-shoot leaves also account for much of the shading. With slender-spindle trees, the branches are usually much closer together, with only small gaps in the canopy, than with taller trees. This results in a high density of foliage in the tree canopy. With moderate to vigorous growth, these gaps can be closed very quickly in the season leading to poor fruit colour and quality if the trees are not summer-pruned (Corelli and Sansavini, 1989). Our experience with cultivars like 'Empire' indicates that summer pruning of slender-spindle trees is essential for good fruit colour. Sansavini *et al.* (1981) found that, under vigorous growth conditions, light levels in the lower part of the canopy of a slender-spindle multi-row system were lower than in a medium-density palmette hedgerow. In one of our orchard trials of five different systems, we found that the fruit quality and economic returns in the eighth year were best for the Y trellis and were poorest with the triple-row slender-spindle system, despite it having the highest yield. The challenge with slender-spindle trees is to combine the correct vigour-control techniques and pruning with spacing. Incorrect choice of tree spacing or excessive vigour can result in excessive shade, due to the limited area allotted to each tree.

Planar canopies have been developed to overcome the problems of light penetration into thick canopies. Since the foliage and limbs are restricted to a single plane, these tree forms usually have a dense canopy, which is essentially non-transmitting. The rule of thumb of 1 m of light penetration does not hold in this case. With the horizontal planar canopies, such as the T or Ebro trellis, there is a drastic reduction in light levels from the top to the bottom side of the canopy. Ferree *et al.* (1989) reported that, with the Lincoln canopy (T trellis), severe dormant pruning was required for good light transmission through the canopy, with more typical moderate pruning having very low transmission values. With the Ebro trellis,

Tustin *et al.* (1989) and Warrington *et al.* (1996) found low light transmission through the top layer of the trellis, resulting in excessive shade of the lower layers. These horizontal canopy systems, which were developed for mechanization of the harvest, suffer from the horticultural problems of excessive upright shoot growth from the top side of the trellis. This increases the level of shading and, in the case of the Ebro trellis, can result in complete closure of the space between tiers. Our experience in New York with red cultivars, such as 'Empire', shows that fruit colour with horizontal trellises is poor and canopy development has been slow due to the flat limb orientation.

Inclined V- or A-shaped canopies were also developed for mechanical harvest, but they do not have the vigorous-shoot problems of the horizontal canopies. In addition, light exposure to the bottom side of the canopy depends both on light transmission through the canopy and light energy coming through the open gaps at the top of the canopy arms. In our study described above, a dwarf version of a Y-shaped hedgerow had very good light exposure at 14 DAFB, with no part of the canopy receiving less than 30% of full sunlight (Fig. 15 16). By 44 DAFB, there was a strong gradient of light through the canopy, with the interior of the Y receiving greater than 50% full sun, while the underside of the Y received less than 30%. By 74 DAFB, only the top interior portion of the Y was well illuminated. Summer pruning, which consisted of removal of unwanted watersprouts in the interior of the Y, increased the exposure at the centre of the Y. However, the underside of the trellis remained below 30% full sun. This was due to closing of the canopy of adjacent rows, which allowed little light between the rows. Our experience indicates that, when the canopies of adjacent Y-trellis rows touch, fruit colour and quality on the underside of the trellis decline. A minimum of 1.5 m of open space between the Y arms of adjacent rows is required for good fruit colour.

Thin vertical canopies receive light exposure from both sides of the canopy and so should have good light distribution within the canopy. Ferree (1980) reported that a pal-

mette hedgerow had better light distribution into the canopy than did slender-spindle, interstem or pyramid-hedgerow trees. The trellis also had greater crop density and greater efficiency than the other systems. If canopies are kept thin, the vertical-trellis canopies generally produce excellent fruit quality. However, with wide palmette-trellis hedgerows, Ferree *et al.* (1989) found light transmission to be similar to that of the slender spindle.

In general, planting systems that result in interior canopy shading when the trees are mature, such as the triple-row or overly vigorous close plantings, will have lower fruit quality than those that maintain good light distribution throughout the tree canopy, such as the vertical axis, palmette trellis and Y trellis. Good light distribution can be achieved in older trees if the top of the tree is kept narrower than the bottom of the tree and if there is a good balance between vegetative growth and cropping. For conic systems, such as vertical axis, slender spindle or the traditional central leader, maintaining a conic shape as the trees age is critical to maintaining good light exposure, fruiting and fruit quality in the bottom of the tree. In our experience, the best way to maintain good light distribution within the canopy as the tree ages is to remove whole limbs in the top of the tree once they grow too long, rather than shortening back permanent scaffold branches in the tops of trees. Traditionally with the central-leader system, permanent tiers of upper branches were developed. A successful approach to managing the tops of trees has been annually to remove one or two large upper branches completely. When this style of pruning is repeated annually, the top of the tree can be composed completely of young fruitful branches. The younger branches do not cause as much shade as larger, older branches and are naturally shorter than the bottom branches, thus maintaining the conic shape of the tree. When this strategy, which is termed limb-renewal pruning, is employed with high-density systems, such as vertical axis, slender spindle or Y trellis, good light distribution can be maintained over the life of the tree.

15.8.5 Balance between vegetative growth and cropping

The successful management of apple trees in any high-density system depends on maintaining a balance between vegetative growth and fruiting. If vigour is too low, excessive fruiting results, fruit size declines, biennial bearing increases and trees fail to fill their allotted space soon enough to make the orchard profitable. If vegetative vigour is excessive, then flowering and fruiting are reduced and containment of the tree to the allotted space becomes problematic. The successful balance of vegetative vigour and fruiting results in 'calm' trees that produce heavy annual crops and require only a light annual pruning. Pruning and tree-training strategies are the primary management methods, along with fertilization strategies, that are used to achieve a balance between vegetative growth and cropping throughout the orchard's life. Pruning, training and fertilization strategies must be compatible with the tree spacing, cultivar and rootstock. Often growers use pruning techniques that are not compatible with high-density systems. For example, pruning strategies that use heading cuts can stimulate excessive tree growth and vigour, reduce fruiting and ultimately delay profitability.

During the development years of an orchard's life the balance between vegetative growth and cropping of most modern high-density systems is based on the principle of minimal pruning during the first 4 years. No heading cuts should be done to the leader except at planting if the tree planting density requires significant tree growth to fill the allotted space. This heading cut serves to balance the top of the tree with the root system to ensure good growth in the first year. Thereafter, the maximum growth is achieved with no pruning. For the first 4 years, pruning should be limited to the removal of unsuitable branches, such as those lateral branches that are as large as or larger than the leader. Cook and Strydom (2000) have suggested a 3:1 pruning rule where the leader should be three times the diameter of any of the lateral branches in the upper part of the tree. They have suggested that limbs

that are larger than the 3:1 rule should be removed early on to preserve a hierarchy of branch and leader diameter.

The most important method of inducing cropping and reducing induced juvenility is tying down of the scaffold branches to induce cropping. In some systems, this is limited to the first tier of branches (vertical axis, slender pyramid and HYTEC), while, in other systems, upper branches are also tied down (SolAxe). In most climates, if pruning of branches is minimized, often crop load will bend branches down and a natural balance between vigour and cropping will be established without additional limb positioning. In vigorous and/or warmer climates where winter chilling is insufficient, limbs often become too large before they set sufficient crop loads to bend the branches down. In these climates, the tying down of all vigorous limbs must be done annually for the first 3–5 years until the tree settles down and begins to crop heavily (Cook and Strydom, 2000). However, in most traditional apple-growing areas, growers often invest too much money in limb positioning, which should be limited to only what is essential in the first 2 years. Thereafter, the precocity of the rootstock induces heavy cropping and a natural balance is established.

Management of cropping during the first 4 years to avoid biennial bearing is critical to maintaining a proper balance between vegetative growth and cropping as the trees begin to bear. With precocious dwarfing rootstocks, young apple trees can often over-set in the second or third year, resulting in biennial bearing as early as the fourth year. This then results in increased vigour in the fourth year, just when the trees have filled their allotted space and when reduced vigour is needed. Cultivars differ in their biennial bearing tendency and this must be incorporated into the crop loads allowed on young trees. In general, we recommend crop loads of five to 15 apples per tree in the second year, 30–60 apples per tree in the third year and 100–120 apples per tree in the fourth year. Within each year, the low end of the range should be used for low-vigour trees and the high end of the range for high-vigour trees.

As the orchard reaches maturity, containment pruning of the canopy is critical to maintaining trees within the allotted space. Pruning strategies based on shortening or stubbing back permanent branches that outgrow their allotted space are not generally as successful as limb-renewal pruning strategies. This is partially because the most productive fruiting wood is cut off when a branch is shortened. In addition, stubbing cuts stimulate localized vigour on the affected branches. In our studies on how to manage the canopies of both low- and high-density systems, treatments where branches were shortened to maintain the conic shape of the tree resulted in unacceptable yield reductions and excessive vigour compared with an unpruned control. A more successful approach has been to annually remove one or two large upper branches completely and develop younger replacement branches. To ensure the development of a replacement branch, the large branch should be removed with an angled or bevelled cut so that a small stub of the lower portion of the branch remains. From this stub a flat weak replacement branch often grows. If these are left unheaded, they will naturally bend down with crop. They are naturally shorter than the bottom branches, thus maintaining the conic shape of the tree without stubbing cuts. This type of pruning does not stimulate vigorous regrowth. Using the 3:1 pruning rule of Cook and Strydom (2000), where limbs that are larger than one-third the size of the leader are removed, can result in a tree with primarily small fruiting branches in the top of the tree. Our recommendation is to begin removing one or two whole limbs in the top of the tree once the tree is mature (year 6–7). This allows moderate pruning each year and is a method to contain tree size. It also maintains good light distribution in the canopy without inducing excessive vigour. On trees with overgrown tops that need to be restructured, moderate renewal pruning (one or two large upper branches annually) for a 4–5-year period can eliminate all of the large branches in the top of the tree. This style of pruning can be applied to almost all systems. Even those systems based on permanent branches can benefit from renewal pruning as they age.

15.9 Orchard Management Practices for Successful High-density Orchards

There are many additional factors that must be considered to make the new high-density orchard truly profitable. In one of our studies, we obtained yield data from ten grower orchards of the same high-density vertical-axis system. There was considerable variation in early yields. Those orchards with low yields could almost always be traced to poor tree growth in the first 3 years, which delayed the time when the trees achieved canopy closure. If trees do not grow well in the first few years, excessive flowering and fruiting occur, which stunts the tree. Such orchards often fail to fill the allotted canopy space and continue to have moderately low yields for many years. Management variables that have a large impact on the growth and performance of young trees over the first 5 years include the following

15.9.1 Soil and site selection

Site and soil factors initially determine whether an orchard should be planted at all (see Chapter 11). There are many orchards in existence today that would not have been planted had growers carefully considered the real costs of planting in that site. Site and soil characteristics that result in crop or tree loss rapidly reduce the profitability of an orchard block. This is especially true with high-density orchards. If the site selected has the potential for spring frosts, winter freezes, fruit russet, tree loss or hail, resulting in crop loss during these early years, then the new high-density block will not be profitable. Unsuitable sites cannot usually be modified economically to prevent finish and fruit-quality problems. In almost all cases, if growers planted only their best sites with new high-density orchards and left the undesirable sites unplanted, their profitability would be improved. Often significant amounts of money are wasted on poor sites. Soil characteristics that result in excess water or lack of water are also important, but can sometimes be modified through choice of rootstock or mechanical methods, such as drainage, irri-

gation or ridging. The fruit grower needs to know whether the cost of modification will bring economic returns. 'Soil strength' or fertility can sometimes be important, especially with vigorous and poor-colouring cultivars. Excess fertility often results in soft and poorly coloured, unmarketable fruit. This fruit is not suitable for extended storage or export and will result in lower profitability, since alternative markets are less profitable. Alternatively, if soil fertility is low and trees grow poorly for the first few years, then profitability will be significantly reduced.

15.9.2 Tree quality

Several studies have shown that larger caliper trees grow more and produce larger yields in the first 4–5 years than do smaller caliper trees (Van Oosten, 1978; Ferree and Rhodus, 1987; Robinson and Stiles, 1991; Sanders, 1993; Wertheim *et al.*, 1995). Large caliper trees that also have lateral branches or feathers produce more than unbranched whips, especially in the second and third year (see also Chapter 6). For very high-density systems that depend on significant second- and third-year yield, feathered trees are vital to the economic success of the system. If growers use small-caliper whips that do not produce fruit until year 4 or 5, often the carrying costs from the extremely high investment of high-density orchards overwhelm the potential returns and negate the benefit of the high tree density for profitability. We recommend that the caliper of trees used in high-density plantings be a minimum of 15 mm and that they have five to ten well-positioned feathers, with a maximum length of 30 cm and starting at a minimum height of 80 cm on the tree. An exception to this recommendation is with the super-spindle or V super-spindle system, where the cost of such high-quality trees makes these systems unprofitable. With these systems, much cheaper trees are needed, and either sleeping-eye budded rootstocks or medium caliper trees with many short shoots are preferred. With these systems, the trees are planted so close together (50–60 cm) in the orchard that very little additional lateral extension growth is needed after planting to fill the space.

15.9.3 Time of planting

Late planting has been shown to reduce tree growth in the first year compared with early spring or autumn planting (Robinson and Stiles, 1991). To maximize tree growth in the first year, growers should plant as early in the spring as possible and, in climates where this is possible, trees should be planted in the autumn.

15.9.4 Weed control

Weed competition can drastically reduce tree growth during the first few years and can cause a failure of the orchard to fill its allotted space, which always results in diminished yield and profitability. Merwin and Ray (1997) have shown that good weed control during the first 3–4 months of a growing season is the most critical time period of the season. In later summer months, if weed control is poorer it is not detrimental to the trees. Thus we recommend that growers provide excellent weed control for the first 4 months of the season for the development years of the orchard (see also Chapter 13).

15.9.5 Irrigation

In many years, dry weather following planting results in water stress of newly planted trees, which can limit tree growth. Often trees undergo stress despite moderate soil-water levels. This is due to the damaged root system of a transplanted tree, which cannot adequately support the top without frequent irrigation. This is especially true with large-caliper feathered trees. Feathered trees produce significant leaf area shortly after planting, which develops a high water demand before the root system can regrow sufficiently to support the trees. Frequent trickle irrigation can help these trees produce good growth in the first year. In humid areas, growers are unaccustomed to installing irrigation or delay its installation until midsummer. We recommend that growers install trickle irrigation soon after planting with high-density orchards that use feathered trees, in order to prevent water stress and maximize tree growth.

15.9.6 Fertilization

Frequent low doses of nitrogen fertilizer, either through the trickle system or on the ground with irrigation, will generally improve tree growth during the first few years to speed development of the canopy. Excessive fertilizer applications near the tree trunk should be avoided, since they can stunt tree growth in the first year due to salt toxicity. Excessive fertilization, especially nitrogen, can cause too much growth, which results in greater pruning costs, delayed flowering, reduced yields and poor fruit quality. Either too little tree growth or too much tree growth will result in failure to achieve expected yields and in decreased fruit quality. Nitrogen management of high-density orchards must take into consideration tree-planting density. For low tree densities, trees must be grown vigorously for several years to fill the allotted space with canopy, and relatively high nitrogen fertilization is desirable for several years after planting. However, as tree density is increased, fewer years are required for the tree canopy to fill the allotted space. In the case of moderately high-density systems, such as vertical axis, slender pyramid or Y trellis, high nitrogen fertilization should only be used during the first 2 years, while the canopy is still expanding. With the higher tree densities used in the slender spindle or V slender spindle, there is little need for additional lateral tree growth after planting when highly branched trees are used, and any vigorous tree growth is counter-productive. In the extreme densities of the super-spindle system, no new lateral canopy extension is needed and nitrogen fertilization in the first few years is avoided in order to enhance cropping and settle the trees down. In general, growers should only grow trees vigorously until the canopy fills the allotted space. Thereafter, low nitrogen fertilization is desirable to keep the trees calm with a balance between fruiting and cropping. Many mature high-density orchards receive excessive nitrogen fertilizer rates, which cause severe canopy management problems (see also Chapter 12).

15.9.7 Soil fumigation

In many cases, tree growth of new orchards that are planted on old orchard land can be improved significantly with soil fumigation. However, the apple replant problem is variable, with some sites showing no benefit from fumigation and others showing significant benefits (Merwin *et al.*, 2001). Ideally, growers should conduct a bioassay before replanting an old orchard site in order to assess the severity of the replant problem and determine the value of soil fumigation. Even with fumigation, almost all old orchard sites produce less tree growth than virgin sites. Thus, tree-planting density should be increased on old orchard sites compared with virgin sites by 20–30%.

If growers properly combine the management variables listed above, they should obtain 50 cm of leader shoot growth in the first year, 75–100 cm of leader shoot growth in the second year and 50 cm of leader shoot growth in the fourth year. If this is combined with minimal pruning and a precocious rootstock, significant production should be obtained in the third and fourth years, which will limit vegetative growth in future years, resulting in a 'calm' tree.

15.10 Economic Comparisons of Orchard Planting Systems

The economic performance of different orchard systems is the final arbiter of the value of a system. Economic measures that are important to fruit growers are the costs of establishment, the cost of mature orchard maintenance, the time required to pay back the investment, the annual cash flows, the discounted cash flows, the net present value of the investment, the annuity of the net present value and the expected life of the orchard. An additional factor, which is difficult to quantify, is the level of financial risk associated with each system.

Most economic studies have shown greater investment costs and annual labour costs with increasing tree density. However, due to higher early yield and higher cumulative yield, profitability is generally increased

with increased tree density (Goedegebure, 1978, 1980, 1986, 1989). However, due to the law of diminishing returns with additional trees per hectare, extremely high tree densities have been shown to be less profitable than more moderate densities. In addition, risk increases with increasing investment, making the very high-density systems higher-risk.

We have evaluated the economic performance of seven orchard planting systems (central leader/M.111, mini-central leader/M.9/MM.111, palmette trellis/M.9, Y trellis/M.26, vertical axis/M.9, slender spindle/M.9, V slender spindle/M.9), using yield and cost data from our research plots in New York State (White and DeMarree, 1992, DeMarree, 1995a,b; Robinson *et al.*, 1996b). The systems represent a range of tree densities, from 500 to 2245 trees ha⁻¹, and a range of rootstock vigour, from MM.111 to M.9. The systems varied in costs from US\$7370 for the central-leader system to US\$28,460 for the V-slender-spindle system (Table 15.11). The large differences in establishment costs were largely related to tree density and the requirement of support for the dwarf rootstocks used in the high-density systems.

Early yield and the maximum yields achieved by each of the seven systems also varied widely. The V-slender-spindle system reached its maximum yield of 42 t ha⁻¹ by year 6, while the central-leader system reached its maximum yield of 35 t ha⁻¹ by year 10. The speed at which each system reached its maximum yield was related to the tree density and to the precocity of the rootstock.

The systems varied widely in how negatively the cumulative cash-flow curve dipped and when the cumulative cash flow curve became positive (Table 15.11). Although the low-density central-leader system required the least investment in tree and establishment costs, the system required a total investment of US\$23,100 ha⁻¹ by the end of year 5 before the cumulative cash-flow curve turned upwards. Many growers have not fully realized that the initial investment in trees and support is only a fraction of the total cost of establishing an orchard and bringing it into production. In the case of the central-leader system, the

cost of trees and support was only 20% of the total investment required. With the higher-density systems, the maximum investment required was higher than with the central-leader system, with the V-slender-spindle system requiring an investment of US\$41,400 ha⁻¹. As tree density was increased, the percentage of the total investment accounted for by tree and trellis costs also increased. Thus, efforts to reduce tree cost and/or support-system cost would have little impact on the total investment required to plant the low-density central-leader system, but would have a large impact on the higher-density systems, especially the V slender spindle. The cumulative cash-flow curve did not break even until the tenth to the 13th year, depending on the system. The vertical-axis, Y-trellis and palmette-trellis systems had the quickest break-even time and the central-leader system the slowest. Thus, although the low-density central-leader system had the lowest initial investment requirement, it had a longer break-even period than did all of the higher-density systems. After 20 years, the Y-trellis, vertical-axis and slender-spindle systems had the greatest cumulative cash flows, with more than double the cumulative cash flow of the central-leader system.

From an investment-analysis perspective, systems can be compared by calculating the internal rate of return on the investment over the 20-year life of the orchard or by discounting the annual net cash flows back to the present value, using a fixed discount rate (net present value (NPV)). We have assumed a real interest rate (or discount rate) of 6%. All of the systems had a positive internal rate of return (IRR), which ranged from a low of 8.2% for the central-leader system to a high of 11.8% for both the vertical-axis and the Y-trellis systems (Table 15.11). The slender-spindle system and the palmette trellis were intermediate at 10%. In general, the higher-density systems had the highest IRR, with the exception of the highest-density, V-slender-spindle system, which had a similar IRR to that of the central-leader system. Examined from the perspective of NPV of the accumulated cash flow over 20 years,

Table 15.11. Costs and profitability of seven orchard systems in New York State (from Robinson *et al.*, 1996b)

System/rootstock	Tree density (trees ha ⁻¹)	Total 1st-year costs (US\$ ha ⁻¹) ^a	Maximum negative cash flow (US\$ ha ⁻¹)	Year of most negative cumulative cash flow (US\$ ha ⁻¹)	Internal rate of return over 20 years (%)	Net present value of accumulated profit over 20 years (US\$ ha ⁻¹)	Net present-value break-even year	Annual equivalent cash flow (US\$ ha ⁻¹)
Central leader/M 7, MM.106 or MM.111	500	7,369	23,117	5	8.2	5,024	17	437
Mini-central leader/M 26 or interstems	680	9,351	24,227	5	10.4	11,476	15	1001
Vertical axis/M 26, interstems	1280	17,908	29,670	3	11.8	19,732	13	1720
Y trellis/M 26, interstems	1280	18,150	29,937	4	11.8	19,876	13	1754
Slender spindle/M 9	1500	20,164	34,130	4	10.9	17,943	14	1564
Palmette trellis/M.9	1500	17,016	29,181	4	10.7	14,686	14	1280
V s ender spindle/M 9	2245	28,465	41,406	3	8.8	10,594	16	924

^a Includes land cost of \$2000 ha⁻¹ and pre-plant land preparation.

our analysis showed that all systems were profitable. The NPV of accumulated profit after a 20-year life of each orchard system ranged from a high of US\$19,876 for the Y-trellis system to a low of US\$5024 for the central-leader system. With this method of analysis, the central-leader system was clearly the least profitable system. The high-density systems divided into two groups. The most profitable group was the Y-trellis, vertical-axis and slender-spindle systems, while the high-density central-leader, palmette-trellis and V-slender-spindle systems were intermediate in profitability.

There were large differences in the year when the different systems broke even (Table 15.11). The earliest break-even year was year 13 for the vertical-axis and Y-trellis systems. The latest to break even was the central leader (year 17). The break-even year indicates the minimum lifetime of the different systems. Thus, the vertical axis and Y trellis would need to last at least 13 years to recoup the investment and earn 6% on the investment, while the central leader would need to last at least 17 years. Systems with a shorter break-even period allow the grower flexibility of replanting to a different cultivar should market conditions change.

Another interesting comparison is the annual contribution to orchard cash flow, in discounted dollars (annual equivalent cash flow (AECF)) each system would make (Table 15.11). This measure allows the calculation of the area required to produce a US\$100,000 AECF. According to our analysis, 228 ha of the central-leader system would produce a similar AECF to only 57–64 ha of the three best systems (Y trellis, vertical axis and slender spindle). Regardless of which high-density system is chosen, a grower would need less than half the area of high-density orchards compared with the central-leader system to produce a US\$100,000 AECF.

These results are based on obtaining the yields and prices we have assumed. It is important to determine how the results would change if lower prices or yields were obtained. If fruit prices were reduced from US\$0.34 kg⁻¹ to US\$0.26 kg⁻¹, four of the systems would no longer be profitable (cen-

tral leader, mini-central leader, palmette trellis and V slender spindle) (Table 15.12). All of the high-density systems are more sensitive to price than the low-density central-leader system. This means that under low prices they drop the most, but also under high prices they benefit the most. A good example is the situation when a new cultivar brings high prices for the first few years. At US\$0.52 kg⁻¹ during the first 10 years, the best high-density systems (Y trellis, vertical axis and slender spindle) would produce triple the profits of the low-density central-leader system. Under low-price scenarios, the low-density system would become unprofitable before the best high-density systems.

If the yields of each system were reduced by 5 t ha⁻¹ each year, then only the central-leader system would no longer be profitable (Table 15.12). However, if yields were reduced by 10 t ha⁻¹ each year, then only the three best systems would be profitable (Y trellis, vertical axis and slender spindle). If yields were reduced by 15 t ha⁻¹, then all of the systems would be unprofitable. Under this scenario the lowest-density system and the highest-density system would lose the most money. In general, the profitability of the high-density systems is more sensitive to yield than the low-density central-leader system.

If land prices were increased from the relatively low price in western New York of US\$2000 ha⁻¹ to US\$12,000 ha⁻¹, the profitability of all systems would be reduced, but only the low-density central-leader system would become unprofitable (Table 15.12).

In a Dutch study of commercial slender-spindle orchards at different densities, investment cost and labour hours required for planting, pruning and tree training were increased with increasing tree density between 2000 and 4000 trees ha⁻¹ (Goedegebure, 1991, 1993). These increased costs were offset by increased cumulative yield with increasing tree density between 2000 and 4000 trees ha⁻¹. The economic profitability as measured by the NPV of the discounted cash flow over the lifetime of the orchards was improved with increasing tree density (Table 15.13).

Table 15.12. Effect of farm-gate fruit price, yield and land price on profitability of seven orchard systems in New York State (from Robinson *et al.*, 1996b)

System	NPV (US\$) with standard fruit price, yield and land cost ^a	NPV (US\$) with low fruit price (US\$0.26 kg ⁻¹)	NPV (US\$) with high fruit price for first 10 years (US\$0.52 kg ⁻¹)	NPV (US\$) with reduced yields (reduced 5 t ha ⁻¹)	NPV (US\$) with reduced yields (reduced 10 t ha ⁻¹)	NPV (US\$) with reduced yields (reduced 15 t ha ⁻¹)	NPV (US\$) with high land cost (US\$12,000 ha ⁻¹)
Central leader/M 7, MM 106 or MM.111	5,024	-7295	12,404	-927	-7475	-14,676	-2,301
Mini-central leader/ M 26 or interstems	11,476	-2340	22,066	5,298	-1530	-8,681	4,161
Vertical axis/M 26, interstems	19,732	1994	43,123	11,718	3492	-5,429	12,420
Y-trellis/M 26, interstems	19,876	1334	40,981	11,822	3810	-4,809	12,566
Slender spindle/M 9	17,943	72	39,147	9,894	1147	-7,715	10,631
Palmette trellis/M 9	14,686	-1557	34,949	5,891	-2870	-11,886	7,374
V slender spindle/M.9	10,594	-8429	36,429	1,737	-7351	-17,122	3,282

^a Standard farm-gate fruit price = US\$0.32 kg⁻¹; standard land cost = US\$2000 ha⁻¹; standard mature yield for central leader = 35 t ha⁻¹, for high-density central leader = 38 t ha⁻¹, for vertical axis = 42 t ha⁻¹, for Y trellis = 45 t ha⁻¹, for slender spindle = 42 t ha⁻¹, for palmette trellis = 38 t ha⁻¹ and for V slender spindle = 42 t ha⁻¹.

Table 15.13. Labour requirements and economic performance of Dutch slender-spindle orchards at three densities (from Goedegebuure, 1993)

Tree density ha ⁻¹	Cost of trees and support (Dfl ha ⁻¹)	Labour h ha ⁻¹ planting	Pruning h ha ⁻¹ (year 1)	Training h ha ⁻¹ (year 2)	Pruning h ha ⁻¹ (year 2)	Pruning h ha ⁻¹ (year 3)	Pruning h ha ⁻¹ (year 4)	Pruning h ha ⁻¹ (year 5)	Pruning h ha ⁻¹ (year 6)	Pruning h ha ⁻¹ (year 7 and up)	NPV (Dfl ha ⁻¹)
2000	16,680	189	9	45	9	23	47	62	66	91	169,000
3000	22,440	232	11	80	17	31	56	76	77	102	196,000
4000	27,920	275	12	116	25	39	66	90	89	114	223,000

Weber (2000, 2001) reported an economic study of the slender-spindle and super-spindle systems from commercial orchards as grown in the Bodensee area of Germany (Table 15.14). The slender-spindle system had a density of 3000 trees ha⁻¹ and the super-spindle system 6429 trees ha⁻¹. The maximum yield per tree was estimated to be 13.5 kg per tree (40.5 t ha⁻¹) in year 5 with the slender spindle and 7.7 kg per tree (49.5 t ha⁻¹) in year 4 with the super spindle. The super-spindle system used less expensive trees (0.63 Euro less per tree) than the slender-spindle system. Nevertheless, at the end of the first year, the cash-flow value of the super-spindle system was 6614 Euros more negative than for the slender-spindle system. The higher yield of the super-spindle system resulted in a break-even cash flow 1 year later. At the end of the 10th year, the super-spindle orchard had a 2306 Euro ha⁻¹ advantage in NPV over the slender-spindle orchard. The super-spindle system also had a higher picking output of 30 kg h⁻¹ and reduced tree-management labour cost, including tree training and hand-thinning, of 89 h ha⁻¹.

Another Dutch study compared trees at densities from 3000 to 20,000 trees ha⁻¹. Although the best production was achieved between 10,000 and 20,000 trees ha⁻¹ (Fig. 15.13), the best average annual cash flow of 'Jonagold' or 'Elstar' on M.9 rootstock was obtained with a tree density of 6000 trees ha⁻¹, followed by a density of 3000 trees ha⁻¹ (Table 15.15). Profitability was lower with a density of 10,000 and was negative with a density of 20,000 (Balkhoven-Baart, 2000; Groot, 1997). Fruit size and quality were also reduced at the highest tree densities (Wagenmakers *et al.*, 1994). An examination of the effect of fruit price showed that, with prices below 75 cents kg⁻¹, the lower density of 3000 trees ha⁻¹ was the most profitable, while, at very high fruit prices of US\$1.05 kg⁻¹, the higher density of 10,000 trees ha⁻¹ had the highest profitability. If tree price was very high, it favoured the lower densities, while very low tree prices favoured the higher densities.

15.11 Conclusions

The key objective in planning a new orchard with any modern planting system should be to maximize yield in the early years and still effectively produce large yields of high-quality fruit after the trees are mature. The best way to obtain high early yields is to plant high tree densities, irrespective of the tree shape or training system. Successful tree densities under current economic conditions have ranged from 1000 to 7000 trees ha⁻¹. The optimum tree density is primarily an economic issue. In most apple-producing areas, the optimum economic density appears to be between 1000 and 3000 trees ha⁻¹. In some areas with very high land prices, very low tree prices, very high fruit prices and/or government subsidies for planting, the optimum economic tree density appears to be from 3000 to 6000 trees ha⁻¹. In all areas of the world, the traditional low-density central-leader system is not as profitable as the higher-density systems. In addition, the low-density central-leader system generally becomes unprofitable before the high-density systems under poor price or yield scenarios. The super-high-tree-density systems have substantially greater risk than moderately high-density systems, due to the very high investment costs. Often they are only marginally more profitable than more moderate high-density systems, such as vertical axis, slender spindle, slender pyramid, HYTEC or Y trellis. Regardless of the system, growers must understand the high investment cost of planting any high-density system and should limit planting cost and limit the amount of replanting to only 4–5% of their total area in order to maintain a positive cash-flow position for their business.

Among training systems, the V systems have the highest yields and allow a good balance between vegetative growth and cropping. They generally have higher light interception than do conic-shaped systems or flat planar systems. They also provide better light exposure on both sides of fruit than do horizontal branches. V systems also lend themselves to very close in-row spacings and highly rectangular planting designs, which allow for the use of existing equipment

Table 15.14. Economic comparison of slender-spindle and super-spindle orchards in the Bodensee area of Germany (from Weber, 2000)

Training system	Tree density ha ⁻¹	Tree spacing (m)	Price per tree (Euros)	Total establishment cost (Euros ha ⁻¹)	Years to full yield	Mature yield (t ha ⁻¹)	Picking output (kg h ⁻¹)	Training h ha ⁻¹ (years 1–5)	Hand-thinning h ha ⁻¹	Cash flow at end of year 1 (Euros ha ⁻¹)
Slender spindle	3000	1.0 × 3.0	3.17	14,541	5	40.5	130	186	50	–18,812
Super-spindle	6429	0.5 × 2.8	2.54	20,744	4	49.5	160	111	36	–25,426

Table 15.15. Economic performance of 'Jonagold'/M 9 and 'Elstar'/M 9 slender-spindle trees at various densities in The Netherlands (from Balkhoven-Baart *et al.*, 2000)

Tree density ha ⁻¹	Annuity net present value (Dfl ha ⁻¹)
3,000	7,464
6,000	10,853
10,000	3,483
20,000	5,489

in high-density orchards. Despite these advantages, the higher initial costs of the V systems gives them similar profitability to conic systems, such as vertical axis, HYTEC, slender pyramid or slender spindle, when planted at the same density. The greater simplicity of conic systems has meant that most growers are opting for the conic-shaped systems. V systems will probably be better than conic-shaped tree systems under conditions of high sunburn and high winds or where all the fruit must be picked from the ground, since the V systems can intercept more light with short-stature systems than pyramid-shaped systems.

All high-density systems depend on early yields to be profitable. Growers should focus on achieving high early yields by selecting precocious rootstocks and frost-free sites and by obtaining excellent early tree growth. If this is combined with the proper tree training and minimal pruning, high-density systems can be much more profitable than traditional systems. The specific tree-training recipe used in the development of an orchard is less important than the planting density, as long as minimal pruning is employed.

High yield per unit land area at maturity requires high total light interception when

the orchard is mature. This can be accomplished by ensuring that row spacing is not too wide and that tree height is at least 80% of row spacing. High fruit quality when the orchard is mature requires good light distribution throughout the tree canopy. This can best be accomplished by maintaining a narrow canopy shape and through regular limb-renewal pruning.

In the future, the most successful apple growers in the world will need to produce apples very efficiently. This will be done by planting new high-density orchard systems with new higher-quality cultivars. It appears that most of the new orchards will be developed with a vertical conic-shaped tree using M.9 rootstock or M.9-size fire blight-resistant rootstocks. Tree height will be 3–4 m, which maximizes light interception at maturity, with 3–4.5 m between rows. Successful growers will rely on minimal pruning of the leader and the scaffolds in the early years, which will help to maximize early yield. They will utilize a simple support system and a tree-training recipe that is simple and easy to teach to unskilled labour. Lastly, they will manage the canopy of mature trees to ensure good light distribution within the canopy in order to maximize yields and fruit quality

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16 Flower and Fruit Thinning and Vegetative : Fruiting Balance

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16.1 Introduction

Fruit or flower thinning is commercially practised in order to maximize crop value by optimizing marketable fruit sizes, yields, fruit colour, shape and quality, as well as to promote return bloom and tree growth and

maintain tree structure. Thinning also provides more consistent annual yields, which in turn allow the efficient use of packaging, grading, storage equipment and labour. Before the development of chemical thinners, hand-fruit-thinning was routinely practised. However, as labour costs increased

and crop values decreased, hand-thinning became less economic. Currently, hand-thinning is used primarily to supplement chemical thinning – for example, to promote higher fruit quality by removal of small or misshapen fruit (Williams, 1979).

To a processor, apple value is frequently based on increasing increments of 0.6 cm in fruit diameter. Fruit diameter over 6.4 cm is typically used as a benchmark, because larger fruit have a lower proportion of core and peel than smaller fruit. In some years, a 10% 'premium' price may be paid for large volumes if 80% of the fruit are over 6.4 cm in diameter. In other years, fruit below 6.4 cm may have little or no value or are bought at juice price. Juice price is frequently only 30% of that of larger fruit (6.4 cm or greater) that are used for sauce or slices. Fresh-marketed fruit also have a greater value if fruit diameters are within the range of 6.4–8.9 cm. In a 5-year integrated orchard-management study, researchers in North Carolina found that only 41% of 'Delicious' apples met the US fancy-grade standards (Shaffer *et al.*, 1983). The major collage factor was insufficient fruit size (21%), followed by insufficient colour (13.1%). Inadequate fruit thinning soon after bloom was considered responsible for excessive crop loads, which contributed to both small fruit size and insufficient colour. Their data demonstrated the major economic impact associated with excessive crop loads (Shaffer *et al.*, 1983). No data were presented to reflect crop losses in subsequent year(s) due to poor return bloom, alternate bearing or poor tree growth.

The inherent genetics of each cultivar are uniquely different for fruit size, colour, shape, natural fruit set, return bloom and thinning responses to chemicals. Recognizing the individual characteristics of a cultivar is extremely important for maximizing crop value. Certain cultivars are inherently large (such as 'Twenty Ounce', 'Mutsu' and 'Jonagold'), while others ('Jonathan', 'Winesap' and 'Gala') may not achieve 6.4 cm in diameter even when trees are moderately cropped. Additionally, some cultivars, even though heavily cropped in one year, may provide an excellent return bloom and crop regularly ('Gala'), while other cultivars may not flower the following season if trees flowered heavily and carried a moderate crop in the

previous season ('York Imperial' and 'Fuji'). For these reasons, thinning and cultural practices for each individual cultivar must take into account the cultivar's genetic potential and the climate of each production region.

In a strongly alternate-bearing cultivar ('Marigold'), Darbellay (1998) found that the highest sustained yields and maximum crop loads of high-quality fruit were best attained by proper thinning for crop-load control and light pruning to ensure adequate spur and shoot vigour. If trees were not pruned, excessive fruit thinning was required to avoid biennial bearing, low yields and losses due to excessively large fruit. However, severe pruning alone as a method of reducing crop load was not found to be a viable alternative to fruit thinning, due to poor yields, fruit clustering and variable fruit size.

16.2 History of Flower and Fruit Thinning

Over 2000 years ago, Theophrastus (see Thompson, 1957) reported that farmers recognized the tendency of fruit trees to over crop and described the custom of partial crop removal. In 1919, Bedford and Pickering convincingly showed that alternate bearing could be controlled by hand-thinning at the bloom stage instead of fruit thinning 6–8 weeks after full bloom (AFB), which was the commercial practice at the time. In 1934, Auchter and Roberts made the first conscious effort to totally eliminate flowers with common spray materials of the period (calcium or sodium polysulphide, copper sulphate, oil emulsion, zinc sulphate and tar distillates), but defoliation and fruit injury were significant problems with most of the chemicals tested.

16.3 Commercially Important Physiological Effects of Thinning

16.3.1 Return bloom

The timing and severity of thinning in one year may strongly influence cropping for several subsequent years. Singh (1948) reviewed several studies and suggested that fruit thinning practised 30 or more days after

bloom was rarely successful for control of alternate bearing. Strongly biennial-bearing cultivars may routinely be overthinned in order to achieve return bloom, even though greater yields of adequate fruit size could be realized with an earlier thinning time (Harley *et al.*, 1934, 1942; Singh, 1948). Comparison studies of the effects of thinning at bloom vs. 30 days AFB on the subsequent season's return bloom, yield and fruit size were not conducted in the 1940s because hand-thinning at bloom or petal fall was commercially impractical.

Fruit thinning, if sufficiently severe, as late as 60 days AFB was shown to increase blossom-bud differentiation (Haller and Magness, 1933). However, some strongly biennial bearing cultivars, when bloom-thinned, may not have an adequate return bloom especially when the trees carry a full crop to harvest (e.g. 'York Imperial'/M.26 and 'Golden Delicious'/M.26) (Byers *et al.*, 2000b). McArtney *et al.* (1996) found that if 'Royal Gala' (an annual-bearing cultivar) was fruit-thinned 3–4 weeks after bloom, fruit weight was 16% less at harvest and leaf area per tree was depressed by 17%.

16.3.2 Fruit size, quality, colour and pest control

Typically, with alternate-bearing cultivars, thinning in the 'on year' increases yields of the more valuable fruit sizes (Preston, 1954). In the 'off year', fruit in the larger size categories (over 75 mm) frequently command a lower price because they are too large and have more physiological disorders and a shorter storage life. In the 'on year', a significant portion of the fruit are in the smaller, low-priced categories. In large-fruited cultivars, early thinning may result in oversized fruit at harvest and thinning may, therefore, be deliberately delayed in order to reduce fruit size. This delay may improve fruit firmness but have a negative impact on return bloom (Johnson, 1992, 1995). Johnson (1995) reported earlier fruit maturation (as determined by internal ethylene, respiration rates and colour) when trees were thinned at full bloom (FB) + 5 days, but not at FB + 27

days or FB + 39 days. Also, larger fruit that matured earlier were more susceptible to rotting by *Gloeosporium perennans*.

Large fruit from thinned trees are generally more susceptible to bitter pit and internal breakdown and have lower calcium and higher potassium concentrations than do small fruit from non-thinned trees. Furthermore, fruits from thinned trees were found to be less firm and have higher soluble-solids concentration than those from unthinned trees (Sharples, 1964, 1968; Volz *et al.*, 1993). Lafer *et al.* (1999) determined that the optimum crop load should range between 1 and 1.5 kg cm⁻² TSCA (6–9 fruits cm⁻²) for several cultivars. Johnson (1992) suggested that growers should be cautioned against long-term storage of fruit from light trees or overthinned trees and that additional calcium sprays may be needed to reduce storage disorders in some cultivars.

Volz and Ferguson (1999) found that bloom-thinning trees to a single fruit/spur greatly increased fruit size (65%) and had no effect on internal calcium concentration. However, in contrast, thinning alternate clusters only slightly increased fruit size (21%) and reduced calcium concentration by up to 22%. The reduced calcium concentration was caused by an increase in multi-fruited clusters and by lower leaf areas on bearing spurs. For cultivars that suffer from calcium disorders, 1-naphthyl-N-methylcarbamate (carbaryl) may be a more desirable thinner since it is a more selective thinner for removal of smaller fruit from the cluster than is naphthaleneacetic acid (NAA), ethephon or 6-benzyladenine (6-BA).

In 'regular-bearing' cultivars, total yields over a 2-year cycle may be reduced by thinning, but the increased fruit size improves crop value (Preston, 1954; Quinlan and Preston, 1968). Where a theoretical value is assigned to each fruit size, the total crop value is disproportionately influenced by the larger fruit (Table 16.1). In this case, crop value was higher even though total fruit yields were lower due to overthinning at FB + 1 week. For these reasons, the objectives of thinning should be to: (i) eliminate the smallest fruit; (ii) maximize the production of the most valuable fruit sizes; and (iii) prevent biennial bearing.

Table 16.1. Percentage crop, by weight, in five size grades, and yield of 'Sunset'/M.9 trees (2-year mean, 1964/65) (from Quinlan and Preston, 1968).

Thinning time	Percentage crop by size grades					Yield per tree (kg)	Scenario 1 ^a		Scenario 2 ^b	
	< 2 in. (4.4 g kg ⁻¹)	2–2½ in. (4.4 g kg ⁻¹)	2½–2¾ in. (4.4 g kg ⁻¹)	2¾–3 in. (13.2 g kg ⁻¹)	> 3 in. (22 g kg ⁻¹)		Crop value per tree (US\$)	Value as % of control	Crop value per tree (US\$)	Value as % of control
Pink bud	0.0	0.4	9.3	38.2	52.1	9.32	1.58	100	1.54	100
FB + 1	0.0	0.5	7.3	35.3	56.9	10.95	1.92	122	1.88	119
FB + 2	0.0	1.4	18.3	50.8	29.5	12.89	1.81	115	1.70	108
FB + 3	0.1	3.0	35.5	48.3	13.1	13.02	1.43	91	1.21	76
Unthinned	3.0	19.4	46.9	27.1	3.6	14.95	1.11	70	0.65	41

Crop values per tree for scenarios 1 and 2 were added by Byers (2001, unpublished results)

^a Scenario 1. Crop values: < 2 in. – 4.4 g kg⁻¹; 2–2½ in. – 4.4 g kg⁻¹; 2½–2¾ in. – 4.4 g kg⁻¹; 2¾–3 in. – 13.2 g kg⁻¹; > 3 in. – 22 g kg⁻¹.

^b Scenario 2. Crop values: < 2 in. – 0.0 g kg⁻¹; 2–2½ in. – 0.0 g kg⁻¹; 2½–2¾ in. – 0.0 g kg⁻¹; 2¾–3 in. – 13.2 g kg⁻¹; > 3 in. – 22 g kg⁻¹.

Since cell division ceases 4–6 weeks after bloom, fruit from trees thinned near bloom are larger at harvest and have more cells than fruit from trees thinned progressively later after bloom (Denne, 1960, 1963; Sharples, 1968; Goffinet *et al.*, 1995). The greater cortical cell number appears to be the result of an increased rate of cell division and not an extended period of cell division or increased cell enlargement or intercellular space. Even though fruit size is more correlated with increased cortex cell number than with increased cell enlargement, Sharples (1964) demonstrated that severe thinning to less than the optimum cropping 5 weeks after bloom (after the cell-division stage) led to doubling of fruit weight, due primarily to cell enlargement, cell division being only slightly stimulated.

Seed development is essential for apple fruit set in most apple cultivars, but the number of seeds per fruit is considered to have only a minor positive influence on fruit growth. The leaf-to-fruit ratio has by far the greatest influence. Fletcher (1932) showed that hand-thinning of fruit to one fruit per 50 or 100 leaves increased fruit red colour and size, but, when trees were fertilized, red colour was not promoted by thinning. Preston (1954) showed substantial increases in yellow and red colour of 'Duchess Favorite' apples by thinning to 20 or 30 leaves per fruit, but thinning to ten leaves per fruit only slightly affected fruit colour.

Lawson *et al.* (1998) found that hand-thinning fruit to single-fruit clusters reduced oblique-banded leaf-roller damage to apple fruit. Possible explanations were that a single larva would be more likely to damage two fruit hanging in a cluster than a single fruit and/or that there was better pesticide coverage of a single fruit than of a multi-fruit cluster.

Chemical thinners or selective hand-thinning that selects for the 'king' fruit typically improves the length/diameter (L/D) ratio, colour and symmetry of the fruit and allows better exposure to pest-control chemicals of the remaining fruit (Westwood, 1978). Even though fruit shape is generally not correlated with fruit density, plant growth-regulating chemicals (e.g. 6-BA) used for

thinning may directly increase the fruit weight and elongation of 'McIntosh'-type cultivars (Greene *et al.*, 1990) but not those of others, such as 'Golden Delicious', 'Red Delicious', 'Rome' or 'York Imperial' (Greene and Autio, 1994).

16.3.3 Yields

The economic impact of thinning on crop value is comprised of the yield and price of the most valuable size categories averaged over 2 years or more. Even though convincing data are not available, annual bearing trees within an orchard probably average greater yields of optimum fruit sizes than those showing a strongly biennial bearing habit. The expectation is that a few large fruit in the 'off year' and many small fruit in the 'on year' typically would result in less total value. Hoffman (1947) reported that when trees of a biennial cultivar were thinned annually with Elgetol over a 4-year period, the average total yields and fruit sizes were increased.

Parry (1974) demonstrated that removal of all fruit from half of the tree was a more reliable method for avoiding bienniality of 'Laxton Superb' trees than 'whole-tree' cluster reduction and, similarly, Preston (1954) showed that trees that were 'half-tree'-defruited had a larger proportion of marketable fruit over the 2-year bearing cycle. Forshey and Elfving (1977) found that 'McIntosh' apple yields were positively related to fruit numbers, but the increase in fruit size as a result of thinning was proportionally less than the decrease in fruit numbers. Consequently, the total yield per hectare of large, higher-valued fruit was either unchanged or reduced by thinning. In the year of fruit thinning, therefore, the point of diminishing returns may be quickly reached.

16.3.4 Defruiting young trees for tree growth

Trees grown on dwarfing rootstocks typically flower and fruit in the second or third season, whereas trees of similar age grown

on semi-dwarf and seedling rootstocks seldom flower adequately at 4–6 years of age. Early flowering and fruiting of dwarf trees may seriously inhibit tree growth and cause long-term stunting of the tree, which may contribute to reduced tree size, poor tree structure and reduced yields for several years thereafter. For this reason, defruiting of young dwarf trees with chemical thinners or by hand has become a routine commercial practice.

Bedford and Pickering (1916) showed that deblossoming young apple trees for the first two crop years caused trees to bear more heavily for up to 14 years after treatment. The trees were larger and stronger than trees that were allowed to bear in the first two seasons. Maggs (1963) showed that deblossoming caused a threefold increase in new root growth and a twofold increase in trunk cross-sectional area when compared with unthinned trees. Deflowering spur 'Rome' trees increased terminal shoot growth by 52% and trunk circumference by 47% (R.E. Byers, 1992, unpublished results). The application of gibberellins soon after bloom will partially, but not consistently, inhibit flower-bud formation for the subsequent season and will stimulate tree growth in the current season independently of cropping (Unrath and Whitworth, 1991).

16.3.5 Effect of crop reduction on growth and fruiting of bearing trees

Thinning of bearing trees soon after bloom results in greater tree growth and a greater number of spurs with growing bourse shoots when compared with progressively later thinning times (Preston, 1954). Thinning shortly after bloom has been correlated with larger dormant buds, longer flowers, greater spur-leaf area, larger bourse shoots and greater fruit size in the following thinning (Denne, 1963). Maggs (1963) demonstrated that deblossoming trees resulted in more and larger leaves, longer shoot growth, increased trunk thickening and greater root growth; however, cropping trees produced more total dry matter (vegetative growth plus crop) per unit leaf area.

In addition, tree growth was stimulated more when trees were deblossomed than when they were defruited 36 days after bloom. Barlow (1966) demonstrated that thinning promoted an increase in the total number of shoots that grew longer.

By thinning 18-year-old 'Sunset'/M.9 trees at progressively later times – at pink bud, FB + 7 days, FB + 14 days and FB + 21 days – Quinlan and Preston (1968) recorded a 4-year incremental increase in trunk cross-sectional area of 198%, 198%, 193% and 155%, respectively. In addition, total bourse-shoot length per 100 flowering clusters was greatest for the earliest thinning time and, over the 4-year period, was 324%, 221%, 151% and 149% of the control, respectively. Thus the increase in shoot growth per tree was due to the increase in the number of bourse shoots produced and not to their length. These data suggest that early thinning results in a greater number of fruiting spurs and leaves within the whole tree canopy. When thinning was delayed until after bloom, both spur-leaf size and number were reduced (McArtney *et al.*, 1996) and flower-bud size and subsequent fruit size were decreased in the following season compared with thinning at bloom.

16.4 Thinning Chemicals and Their Physiological Effects

Flower thinning or flower-bud inhibition has the advantage of maximizing fruit size, return bloom and yield, and allows additional time to reduce further as necessary the crop by post-bloom chemical- or hand-thinning practices. The primary disadvantage of flower thinning is the potential for subsequent damage to flowers or fruit by spring frosts. Secondly, the environmental conditions that have an impact on pollination, fertilization and fruit set subsequent to thinning are unpredictable (Batjer, 1965). Flower-bud inhibition in the previous season or thinning at tight cluster or pink may have some utility for small-fruited cultivars, those that flower heavily and those that are typically biennial bearers.

16.4.1 Pollinicides

Pollinicides provide an additional physiological mechanism for thinning apples that is basically different from that of hormone-type thinners and which could be used under cool conditions where the effectiveness of hormone-type chemicals is greatly reduced.

Elgetol (sodium-4,6-dinitro-*ortho*-cresylate) (DNOC) became the first commercially important apple flower-thinning agent (Batjer and Thompson, 1948; Williams, 1979) and remained so for over 40 years until its Environmental Protection Agency (EPA) registration was cancelled in 1990. Hildebrand (1944) showed that elgetol inhibited fruit set when applied as much as 32 h after pollination, when pollen-tube growth was approximately midway down the style.

Elgetol thinning at bloom was considered to be a part of a total-thinning programme in the western USA that was essential for maximizing fruit size and return bloom (Williams, 1993a,b, 1995). The cancellation of elgetol registration prompted the search for a replacement chemical (Williams, 1994), which, based on the western US elgetol use pattern, could only be marginally justified in regard to new chemical registration costs.

Research has shown that elgetol, when applied just before wet and humid periods, caused fruit and foliage injury, with erratic effectiveness as a thinner. In addition, unpredictable weather during pollination and fertilization further contributed to unpredictable thinning related to a variable number of flowers setting fruit. Several chemicals that were effective as peach thinners were found to be effective apple-bloom thinners (Endothall, ammonium thiosulphate (ATS) and long-chained fatty acids) (Byers and Lyons, 1985; Byers *et al.*, 1985a,b; Williams, 1993a, 1995; Southwick *et al.*, 1996; Bound and Jones, 1997; Byers, 1997; Fallahi, 1997). The use of ATS for flower thinning has been commercially practised in the USA for over 10 years and is the standard material used in much of Europe.

Because the apple receptacle and spur leaves are exposed to spray chemicals before, during and after flower opening, caustic bloom-thinning sprays may cause some fruit

scarring and leaf injury. Pelargonic acid (57% plus 3% related fatty acids with a total 60% a.i.; 'Thinex'), YI-1066 and sulphcarbamide-1-aminomethanamide dehydrogen tetraoxosulphate (79% a.i.; 'Wilthin') caused more fruit injury than mono-*N,N*-dimethylalkylamine salt (Endothall 4.793% a.i., 5.5% acid equivalent, TD 04EC 2337-03) or ATS (60% ATS or 55% ATS; 'Thinset') in several experiments (Williams, 1993a; Byers, 1997; Fallahi, 1997). Although the amount of fruit injury is usually limited, the potential for fruit scarring may limit the use of certain chemicals for fresh-market apples. The more caustic chemicals could be used, for example, where fruit are grown for processing, where surface injury would not be of economic consequence. Even though a small percentage of fruit were marred by some of the chemicals, the resulting benefits of increased fruit size and return bloom may offset the negative effects. Because the king flower produces the largest and most typically shaped fruits (for most cultivars), it would seem most desirable to apply bloom thinners in the late bloom to inhibit fruit set of the lateral flowers and especially flowers on annual growth since these produce small fruit. However, tests indicate that injury increases with later applications and higher chemical rates (Byers, 1997). Another disadvantage of pollinicides is that the application window requires a short span of a few hours to make single or multiple applications. Future research should focus on improved spray thinning chemicals that reduce or eliminate fruit russet and leaf injury in single or multiple applications, since each chemical may have differences in residual half-life and cumulative phytotoxicity when used in multiple applications.

The search for pollination/fertilization inhibitors that do not affect fruit finish deserves considerable attention for fruit destined for the fresh market. Certain fungicides such as Captan and Triforine (Funginex) are strong inhibitors of pollen-tube growth *in vitro* (Fell *et al.*, 1983). These chemicals are also known for their non-phytotoxic effects to fruit and foliage. There has been speculation that fungicides that inhibit pollen-tube growth *in vitro* might reduce fruit set in the

field if applied at bloom (Fell *et al.*, 1983, Gomma, 1989). Preliminary data indicate that Captan reduced fruit set when applied with a handgun during bloom but not when applied with an air-blast sprayer (R. E. Byers, 1993, unpublished results). Since fruit produced by late bloom (flowers borne laterally on the previous season's terminal growth) are frequently smaller than those produced by flowers borne on spurs, fungicides applied at early petal fall could be beneficial for eliminating fruit set of late flowers, thereby improving fruit size. Screening pollination inhibitors for use on late-opening flowers and that do not cause russetting of earlier-formed fruit is important.

At bloom, the percentage of flowers open between adjacent trees in the same row may range from 40 to 95%. In addition within the same block, terrain, microclimates, cultivar, strain, and soils can also affect flower opening, pollen tube growth rate, natural fruit set; and thus, if a pollination inhibitor is applied to all the trees in the block at the same time, the potential exists for creating wider differences in fruit set than existed naturally. Multiple applications applied at intervals of 2-3 days may reduce thinning variation caused by differences in flower opening, but test results have not been consistent (Byers, 1997).

16.4.2 Gibberellin for inhibition of flower-bud formation

Since heavy flowering in one year inhibits the growth and development of the bourse flowers in the subsequent season, partial inhibition of flowering with gibberellin sprays may promote fewer and larger flowers. McCartney (1994) demonstrated that a single spray of gibberellin A₃ (GA₃) or GA₄₊₇ at full bloom in the 'off year' reduced the subsequent season's flowering in the 'on year' and the severity of biennial bearing of 'Braeburn' trees. Increasing concentrations of a gibberellin spray linearly decreased flowering the following year and promoted flowering 2 years after application. Several experiments have shown GA₇ to be more effective than GA₃ and that GA₄ is ineffective

for inhibition of flower-bud formation (Dennis and Edgerton, 1966; Tromp, 1982, McCartney and Li, 1998). Tromp (1982) found that GA₄₊₇ more effectively reduced flowering than did GA₃ on both spurs and 1-year-old shoots. However, Marino and Greene (1981) found that GA₃ was more effective on 1-year-old shoots and GA₄₊₇ was more effective on spurs at decreasing flower-bud formation. Applications of gibberellins must be made at bloom or shortly thereafter to be effective on spurs, but applications up to 60 days AFB are effective on 1-year-old shoots (Tromp, 1982). Gibberellins used to reduce russetting of 'Golden Delicious' fruit have also shown some inhibition of flower-bud formation (Meador and Taylor, 1987; Greene, 1993). It is believed that gibberellins interfere with the early phases of bud primordia development long before flower buds are microscopically visible. Although less effective for flower-bud inhibition, GA₃ may be a better choice economically, since the price of GA₄₊₇ may be five times that of GA₃.

To maximize tree growth, Unrath and Whitworth (1991) attempted to completely inhibit flowering of young non-bearing 'Red Chief Delicious' trees. In one experiment, multiple applications GA₄₊₇ at rates of 250 mg l⁻¹ or 500 mg l⁻¹ reduced flowering by 95% and 99%, respectively. In two other experiments, similar treatments gave very little or no suppression of return bloom, however, the timing of GA₄₊₇ applications may have been too late.

In bearing 'York Imperial'/MM.111 trees, a single spray of GA₃ in the 'off year' provided more regular cropping for 4 subsequent years (Byers *et al.*, 2000b).

16.4.3 Hormone-type plant-growth regulators (PGR) for bloom and fruit thinning

Because hormone-type thinners are less effective during bloom, they have been primarily used for fruit thinning, in contrast to pollination inhibitors, which have been used for flower thinning (Williams, 1979, Wertheim, 1997; Dennis, 1986; Dennis, 2000). Hormone thinners are not dependent

on flower opening and are less injurious to fruit or foliage than are many caustic pollinicides. Since insecticides such as carbaryl, dylox, morestan and oxamyl kill wild or domesticated pollinating insects, certain hormone-type thinner combinations should not be applied during bloom. The value of very early thinning with chemicals such as NAA, 2-chloroethylphosphonic acid (ethephon), carbaryl (XLR formulation), 6-BA or Accel at petal fall is substantial (Jones *et al.*, 1989, 1990, 1991; Williams, 1993b; R.E. Byers, 1994–1999, unpublished results). Pollinicides, however, provide an alternative to hormone thinners when the effectiveness of hormone thinners is limited due to low-temperature conditions.

Chemical thinning has typically been quite variable, depending on factors such as the orchard, cultivar, location and year. Although 50 possible factors might influence the effectiveness of NAA thinning, most are non-significant (Hennerty and Forshey, 1972). Of all these factors, the most significant was a positive relationship between the number of fruits removed and the number of fruits naturally set on the tree. At the spray date, fruit set was positively related to the nitrogen content of the spur at full bloom and to shoot vigour at green tip, but negatively related to spur vigour. Fruit thinning was not related directly to tree vigour, soluble or total nitrogen or soluble, reserve or total carbohydrates. The physiological tree 'condition' was thought to have a greater effect on flowering and fruit set than the overall response of the tree to thinning chemicals.

Foliar penetration and movement of hormone-type thinners to their site(s) of action are required for fruit thinning to be achieved. The cuticle on the under leaf surface permits approximately tenfold greater NAA penetration than the upper cuticle (Norris and Bukovac, 1969). Penetration of NAA or naphthalene acidimide (NAD) is highly dependent on temperature, especially between 15 and 25°C, and is also positively correlated with increasing humidity. D.W. Greene (1998, personal communication), however, has pointed out that ¹⁴C-NAA

uptake under increasing temperature and decreasing humidity conditions throughout the day has opposing influences, which appear to compensate for one another.

The fundamental mechanism(s) by which a hormone thinner causes fruit abscission is not known, but Ebert and Bangerth (1982) suggested that a major factor in the mode of action of carbaryl, ethephon and naphthaleneacetamide (NAAm) is a reduction in indole-3-acetic acid (IAA) transport. Williams (1981) found that NAA and carbaryl caused elevated ethylene levels in apple fruits similarly, but NAA caused a greater stimulation of ethylene in leaves. Aminoethoxyvinylglycine hydrochloride (N-(phenylmethyl)-1H-purin-6-amine, or AVG), an inhibitor of ethylene biosynthesis, applied before or after either NAA or carbaryl suppressed ethylene and abscission of fruit, but, when either ethephon or ethylene gas was applied to the trees, fruit abscission was not inhibited. Ward *et al.* (1999) recently found that cellulase activity did not appear until approximately 4 days after the application of carbaryl + ethephon, but fruit diameter, water potential and starch were reduced within 2 days after treatment. Since low light further stimulates fruit abscission, the role of photosynthates for fruit retention may be fundamental hormone to the action of chemical thinners (Byers *et al.*, 1991).

16.4.3.1 Naphthaleneacetic acid

In 1941, auxin-type sprays (NAA and NAD) were found to cause fruit abscission (Burkholder and McCown, 1941), but their commercial value was not apparent until the early 1950s. Cultivars that reached maturity during early, mid- and late summer were typically thinned by the more mild NAD, because NAA caused foliage injury, inhibition of fruit growth, premature ripening and fruit splitting. In contrast, cultivars that mature in the autumn were typically thinned with NAA (Batjer, 1965), since many of these detrimental effects were not observed.

NAA alone has not caused specific fruit-finish or shape problems. To reduce the negative effects of NAA on fruit growth, lower

rates of NAA (2.5 mg l^{-1}) in combinations with carbaryl, oxydemeton and/or adjuvants have given excellent thinning in most years. Combinations of NAA and carbaryl are widely used for chemical thinning of many apple cultivars, but NAA may cause serious overthinning and/or dwarf fruit in certain cultivars (Rogers and Williams, 1977). Several papers and reviews suggest that many cultural and environmental factors influence NAA thinning, and local and regional conditions are important to determining recommendations (Westwood, 1978; Dennis, 1979; Lehman *et al.*, 1987; Byers *et al.*, 1990b). NAA and NAD alone or in various combinations with gibberellins were found to increase the incidence of dwarfed fruit (pygmy fruit) and retard fruit growth in most spur 'Delicious' and 'Fuji' strains (Henderson and McBurnie, 1943; Rogers and Williams, 1977; Byers, 1978; Westwood, 1978; Byers *et al.*, 1982).

Soon after application to leaves, ^{14}C -NAA was found in apple fruits and seeds (Williams and Batjer, 1964). Luckwill (1953) suggested that seed abortion may be responsible for fruit abscission. However, Luckwill and Lloyd-Jones (1962) recovered only 0.2% of ^{14}C -NAA applied to apple leaves from seeds after an interval of 5 days, and all of the applied NAA was metabolized. This suggests that fruit abscission is not due to the direct toxic action of NAA to seeds. Four days after placing NAA on the upper leaf surface, 80% of the NAA was lost (presumably to ultraviolet (UV) light destruction), 10% was found within the leaves and 10% was still on the leaf surface. This neutral metabolite in the leaf was devoid of auxin-like activity, but, since non-auxin compounds also cause fruit thinning, it is possible that it had thinning activity. In addition, since NAA has been shown to thin both seeded and seedless fruit of one cultivar (Dennis, 1970), the seed-abortion theory is not likely to be the mode of thinning action of NAA.

NAA has been shown to cause an increase in fruit ethylene production (Walsh *et al.*, 1979). The leaf epinasty response caused by NAA is a typical ethylene response, but, in Schneider's (1975) work, ethylene evolution

followed the negative effect of NAA on fruit reducing sugars; thus, ethylene was not thought to be the cause of NAA-induced abscission. However, Curry (1991) demonstrated that NAA promoted ethylene evolution very soon after application. He proposed that 1-aminocyclopropane-1-carboxate (ACC) produced in the leaves may be transported to the abscission zone, where it is converted to ethylene and causes fruit abscission.

Stopar *et al.* (1997) showed that NAA suppressed photosynthesis by 10–24% over a 15-day period and was concentration-dependent. NAA sprays have been shown to reduce stomatal opening (Snaith and Mansfield, 1984) and result in less reducing sugars and sorbitol in fruit (Schneider and Lasheen, 1973; Schneider 1975, 1977). Since shading trees for a 2–3 day period caused substantial fruit drop (Schneider, 1978; Byers *et al.*, 1990a,b), reduced photosynthesis is known to cause fruit thinning. A long period of reduced photosynthesis caused by NAA (Stopar *et al.*, 1997), along with low environmental light conditions, strongly supports the view that fruit abscission involves energy-driven processes that operate over a 2- or 3-day period.

16.4.3.2 Carbaryl

In 1958, carbaryl was found to be a mild thinner (Batjer and Westwood, 1960) and was rate-insensitive above 750 mg l^{-1} (Southwick *et al.*, 1964; Way, 1967). In addition, multiple applications typically did not increase thinning (Byers and Carbaugh, 1991). Most spur 'Delicious' strains normally set heavy crops, and carbaryl alone was found to be inadequate for thinning (Henderson and McBurnie, 1943; Rogers and Williams, 1977; Byers and Carbaugh, 1991). The effectiveness of carbaryl was increased by the addition of superior spray oil (Byers, 1978; Byers *et al.*, 1982), possibly because carbaryl is more soluble in oil than in water, but oil is also known to inhibit photosynthesis mildly. Carbaryl is not thought to affect return bloom directly.

Under certain undetermined environmental conditions, carbaryl may cause fruit

injuries, characterized by lenticle spotting. If there is substantial injury, the fruit may be scarred and misshapen on the lower side and/or calyx end, particularly with spur 'Delicious' (R.E. Byers, 1981, unpublished results; Byers *et al.*, 1982, 2000a; R.C. Unrath, 1998, unpublished results). High rates or multiple applications of carbaryl plus adjuvants (oil or surfactants) or combinations with other fruit thinners, such as carbaryl plus Accel (6-BA + GA₄₊₇) plus oil, may cause additional injury. Artificially shading trees on the day of the carbaryl spray or every third day substantially increased injury. At application time, small fruit (10 mm) seem to be more susceptible to injury than larger fruit (17 mm) sprayed later in the spring. The injury may be severe in some years, but not others (Byers *et al.*, 2000a). The cause for year-to-year injury variation has not yet been determined (Plate 16.1).

Williams and Batjer (1964) found that fruit were more susceptible to abscission if only fruit were treated than if only leaves were treated. ¹⁴C-carbaryl applied to fruit moved into the vascular tissues of the fruit (the proposed site of action). Knight (1983) believed that the bourse-shoot leaves could absorb and translocate sufficient carbaryl to cause fruit thinning and this proposition was further supported by Byers *et al.* (1991), who found that treating either leaves or fruit caused fruit thinning.

Carbaryl is widely known to kill predators of phytophagous mites and the use of carbaryl frequently causes mite populations to fluctuate out of control (Byers *et al.*, 1982). Its use, therefore, presents difficulty in maintaining integrated pest management (IPM) programmes (Hislop and Prokopy, 1981, Elfving and Cline, 1993a), particularly if two applications of carbaryl are made. The carbaryl formulation Sevin XLR has been found to be less injurious to mite predators and bees and thus has been successfully used at petal fall for thinning. The addition of low rates of a 70 s, delayed dormant, superior oil (0.25–0.5%) to carbaryl thinning sprays has provided some initial suppression of mite populations (R.L. Horsburgh and L. Cobb, 1989, unpublished results, Biggs *et al.*, 1999).

16.4.3.3 Oxamyl

Vydate, a systemic carbamate, at its highest insecticidal rate was found to be a mild thinner similar to carbaryl (Byers *et al.*, 1982). Oxamyl used as a thinner did not affect mite populations, but did increase side-russet development in 'Golden Delicious' fruit and in other cultivars prone to this problem, furthermore, lenticle enlargement may also occur (Byers *et al.*, 1982). Certain combinations, such as Oxamyl + Accel + oil, may cause substantial red-colour inhibition of spur 'Delicious' fruit. Oxamyl alone under certain environmental conditions (not yet defined) may inhibit red colour between lenticles and cause a red-spot appearance around the lenticles on the fruit surface (R.E. Byers, 1995, unpublished results).

16.4.3.4 Ethephon

Ethephon is considered a very dose- and temperature-dependent chemical thinner (Koen and Jones, 1985) and is the only material that can effectively thin from bloom through to a stage when fruit are larger than about 25–30 mm in diameter (Veinbrants and Hutchinson, 1976). It is typically used when earlier chemical thinning sprays have failed to thin adequately. Considerable experience is needed to use this chemical most effectively, since ethephon can be erratic and can trigger total fruit drop. Information indicates that the volume of water and method of application may have more influence on thinning than high temperature or chemical concentration (Unrath, 1978; Jones *et al.*, 1990, 1991). In Virginia, spur 'Delicious', 'York Imperial', 'Gala' and 'Winesap' are less responsive to ethephon, while 'Golden Delicious' and 'Rome' are more easily overthinned than most other cultivars (R.E. Byers, personal observations). Lower rates of ethephon and/or lower volumes of water may be required for these cultivars. Combinations of ethephon and carbaryl have given good thinning of spur 'Delicious' in most Virginia and North Carolina tests (Unrath, 1978; Byers *et al.*, 1990a; R.P. Marini, 1996, unpublished results). Since thinning apples with ethephon can be erratic, registra-

tion and recommendations for using ethephon for thinning need careful consideration and coordination between the chemical company, state and federal registration agencies.

Inhibition of fruit growth has been of concern in several ethephon experiments (Edgerton and Greenhalgh, 1969; Way, 1971; Chiba *et al.*, 1980; Knight, 1980; Ebert and Bender, 1986), but not in others (Veinbrants and Hutchnson, 1976; R.E. Byers, 1980–2000, unpublished results). In Tasmania, ethephon thinning sprays at bloom were found to reduce the L/D ratio, but addition of 6-BA (Cytolin) restored fruit shape (Bound *et al.*, 1993).

Ketchie and Williams (1970) found that ethephon (250–1000 mg l⁻¹) applied in the 1–2-month period prior to autumn leaf drop dramatically reduced fruit set and vegetative-shoot length the next spring. This property might be used to inhibit flowering if applied after harvest in the 'off year' of the biennial bearing cycle. The potential for producing smaller fruit exists but the early flower-bud inhibition may compensate for the direct effect of ethephon on fruit size.

16.4.3.5 Dylox

The Chinese reported that the insecticide Dylox thinned apple fruit and increased ethylene evolution of the fruit (Shen and Sen, 1985). In Virginia, Dylox was found to thin spur 'Delicious' with no detrimental side-effects (R.E. Byers, 1991, unpublished results). This insecticide could be very useful to the apple industry since it has only a minor impact on mite predators and yet it is toxic to leafhoppers, leaf-miners and several other apple pests.

16.4.3.6 6-Benzyladenine

The cytokinin 6-BA has been shown to be an effective fruit thinner and has increased fruit size beyond the thinning effect for 'McIntosh' types (McLaughlin and Greene, 1984; Greene *et al.*, 1990, 1992; Byers and Carbaugh, 1991; Elfving and Cline, 1993a,b; Greene and Autio, 1994; Wismer *et al.*, 1995), but not for other cultivars, such as 'Golden Delicious' and 'Red Delicious' (Byers and

Carbaugh, 1991; Greene and Autio, 1994). The increased fruit size caused by 6-BA has been attributed primarily to a direct stimulation of cell number in the fruit cortex during the cell-division stage and not to cell enlargement (Wismer *et al.*, 1995). 6-BA also has been shown to increase L/D ratio in some cultivars, but may have no effect in others (Jones *et al.*, 1997).

Stopar *et al.* (1997) found that 6-BA had no effect on photosynthesis but Yvan and Greene (2000) found that 6-BA-treated leaves and fruit had higher night respiration rates, thus reducing the total photosynthates available. Although 6-BA sprays have been shown to increase ethylene evolution from fruit before abscission (Kondo and Mizuno, 1989), the magnitude of the ethylene increase was not considered large enough to be the primary cause for thinning (Greene *et al.*, 1992). Unlike NAA, application of 6-BA to the fruit alone caused modest fruit thinning, but the maximum effectiveness was obtained by application to both leaves and fruit (Greene *et al.*, 1992).

Accel, a commercial formulation containing a combination of 6-BA and a low concentration of GA₄₊₇, was registered for thinning apples for the first time in 1995 in the USA. Since gibberellins are known to promote fruit retention, the low gibberellin levels in the Accel formulation may reduce the thinning response (T.L. Robinson, 1999, unpublished results). Cultivars naturally prone to pygmy fruit development should not be sprayed with gibberellins, since a greater number are set (Byers and Carbaugh, 1991; Greene and Autio, 1994). In certain cultivars ('York Imperial'), Accel may increase the number of seedless fruit, even though they may achieve full size (R.E. Byers, 1995, unpublished results).

6-BA combined with carbaryl was found to be more effective than either compound alone and is considered to be one of the most effective chemical thinning combinations (Byers and Carbaugh, 1991). The addition of superior oil to 6-BA or its combination with carbaryl substantially increases effectiveness (Byers and Carbaugh, 1991; Greene *et al.*, 1992). Combinations of 6-BA and carbaryl may cause additional fruit russet of 'Fuji' and 'Golden Delicious' (Bound *et al.*, 1991a,

1993) and, when 6-BA or Accel is combined with Oxamyl plus oil or surfactants, fruit russet in the lenticels and fruit colour may be affected (R.E. Byers, 1995, unpublished results). Trees should not be sprayed with combinations of 6-BA and NAA, since a significant number of seedless pygmy fruit may occur (Bound *et al.*, 1991b)

16.4.3.7 Photosynthetic (PN) inhibitors

Since short periods of artificial shade may cause fruit abscission, photosynthetic inhibitors were screened for their effectiveness as thinning chemicals and for injury to fruit and leaves (Byers *et al.*, 1984, 1985b, 1990a,b). Extremely low rates of herbicides have been found to cause fruit abscission without effects on the remaining fruit or leaves, but others may cause unacceptable leaf injury (Byers *et al.*, 1990a,b). Terbicil was one of the more promising chemicals, but its persistence and leaf injury in some cultivars (e.g. 'Golden Delicious') and the lack of interest from the chemical company for registration have stopped its development as a thinning compound. Most photosynthetic inhibitors available are selected for their persistence for use as herbicides for killing weeds, but short-lived inhibitors, either alone or as an additive to other registered chemical thinners, could be a more useful tool, with less injury to leaves.

Certain pesticides registered for use on apples reduce photosynthesis of apple leaves by 20–30% following multiple applications in the laboratory, such as superior oil (Ayers and Barden, 1975; Ferree and Hall, 1975; Ferree *et al.*, 1976; Wood and Payne, 1984), ethion (Heinicke and Foott, 1966), dicofol (Sharma *et al.*, 1977), fenvalerate and diazinon (Heinicke and Foott, 1966) and other organic phosphates (Pickett *et al.*, 1952; Ayers and Barden, 1975; Ferree and Hall, 1978; Anderson, *et al.*, 1986). Several of these materials in combination with carbaryl potentiate thinning (Byers and Carbaugh, 1991). Since trees sprayed with carbaryl in field experiments have not shown reductions in photosynthesis, inhibition of photosynthesis was not considered the primary cause of fruit abscission (R.E. Byers, 1988, unpublished results)

16.3.3.8 Other chemicals that may influence fruit set

Season-long applications of sterol-inhibiting fungicides (bitertanol, etaconazol or fenarimol) have caused significantly less return bloom when compared with a standard fungicide programme (Latham *et al.*, 1985). Triadinefon was found to affect fruit size, fruit shape and fruit set (Strydom and Honeyborne, 1981). Since sterol inhibitors and plant-growth retardants (Miller, 1988) have been shown to increase fruit set and affect fruit size and shape, they should be evaluated for interference with chemical-thinner efficacy.

Prohexadione-Ca (Apogee®), a new plant-growth retardant registered for apples, has been shown to promote additional fruit set alone (D.W. Greene, 1997, unpublished results), but the fruit appear to respond to various chemical-thinner combinations in a similar way to non-treated fruit (Byers *et al.*, 2000a).

The potential exists for the use of specific pesticides (superior spray oil, liquid lime sulphur, organic phosphates, sterol inhibiting fungicides) or plant growth regulators (ethephon) prior to, or in conjunction with, thinning chemicals to pre-condition trees to make them more responsive to thinning when hormone-type chemicals are applied. This strategy could be very useful for difficult-to-thin cultivars (such as 'Fuji', 'Gala', 'Golden Delicious', 'Pink Lady®') and/or regions where high light or cool conditions make for difficult thinning.

16.5 Adjuvants

The use of a suitable surfactant has been thought to reduce thinning variability caused by widely different environmental conditions (Westwood and Batjer, 1960). In several regions where adjuvants are commercially used, NAA is typically reduced to one-half the recommended rate, resulting in a substantial cost savings. The use of a surfactant with NAA is general practice in some areas (Williams, 1979), but not in others (Robinson *et al.*, 1998). There is evidence to indicate that the chemistry of each thinning compound interacts specifically with each

adjuvant, such that each combination requires testing for its effectiveness.

Several investigators have found that surfactants, superior oil (Byers, 1978; Ebert and Bender, 1986), penetrants, fertilizers (Horsfall and Moore, 1961) and pesticides may increase thinning to varying degrees. Greene and Bukovac (1971) have shown that surfactants may significantly decrease surface tension and increase absorption, but that absorption was not directly related to surface tension. Certain adjuvants alone or in combination with other chemicals may increase thinning by stimulating ethylene production. Oils, liquid lime sulphur and/or organic phosphates may reduce photosynthesis, respiration or some other metabolic mechanism(s).

Greene and Bukovac (1971), using pear-leaf discs in the laboratory, established that surfactants enhanced penetration of NAD through the lower leaf surface, but not the upper. The lower leaf surface absorbed 15-fold more NAD than the upper surface after 48 h. Penetration was not affected by pH, but the pK_a for NAD was 13; thus the NAA molecule was non-dissociated over the pH range studied (pH 3–7 range).

Superior oil and silicone surfactants appear to be among the best of the penetrants used for chemical thinners, but in some tests these compounds increased side and/or lenticel russet or fruit colour if the chemical thinner was prone to producing injury (R.E. Byers, 1995, unpublished results).

16.6 Application Considerations

When chemical thinners were first tested, most were applied with a handgun sprayer at high water volumes to the point of drip from foliage, and the amounts of chemical and water were, therefore, frequently not known. Air-blast spray applications were frequently not as effective as handgun applications. Sutton and Unrath (1988a) demonstrated that handgun applications increased chemical deposits by 60% or more over air-blast tree-row volume (TRV) spray rates and that fruit thinning and disease control were more effective using handgun applications. Herrera-Aguirre and Unrath (1980) found

more uniform thinning results by TRV calibration with ethephon, NAA plus carbaryl and NAA plus ethephon than by using a specific water and chemical rate per hectare, regardless of tree size. TRV calibration of air-blast sprayers was an attempt to maintain an equivalent deposit of chemical and/or water volume per unit leaf area when tree sizes changed (Byers *et al.*, 1971, 1984, 1989, Herrera-Aguirre and Unrath 1980; Sutton and Unrath, 1988 a,b; Byers, 1989).

Several studies have shown that low water-volume sprays were less effective for thinning than were high water volumes (Rogers and Thompson, 1969; Rogers and Williams, 1977; Jones *et al.*, 1988, 1991; R.P. Marini, Virginia, 1995, personal communication). In one experiment, Jones *et al.* (1991) demonstrated that ethephon effectiveness applied with an air-blast sprayer was positively related (linearly) to the water volume; however, increased chemical rates per hectare did not increase thinning. Even though ethephon thinning tests in Virginia have also been inconsistent, the chemical rate appeared to be more important than the water rate per ha in the range of 935 l ha⁻¹ to 3740 l ha⁻¹.

Looney and McKellar (1984) found that spray volumes from 560 to 4400 l ha⁻¹ did not have a major influence on thinning, but better thinning was achieved with reduced spray volumes in two of three experiments. Additional experiments have shown that low-volume (LV) or ultra-low-volume (ULV) sprays for apple thinning can be as effective as high-volume (HV) sprays (Oakford *et al.*, 1991, 1994, 1995). However, the success of LV or ULV sprays is dependent on controlling droplet size by using air-shear machines that produce droplets in the 60–120 µm size range. Most HV sprayers produce droplet sizes greater than 150 µm, which more easily run off the leaf surface. In addition, the high pressure used in many HV sprayers produces a considerable number of droplets that are less than 50 µm and this size does not impinge on the target and the droplets drift significantly. Spraying time where LV sprayers are used can be reduced by as much as 60% over that of HV spraying, and, according to Oakford *et al.* (1995), chemical rates may be reduced to some extent. Bound

et al. (1997) increased the chemical-thinning effectiveness of conventional air-blast sprayers by using a redesigned nozzle that produced finer droplets at low volumes. These nozzles (developed by Delavan-Delta Inc.) produced a greater number of optimum-sized droplets than the traditional HV hydraulic-sprayer nozzles.

In controlled laboratory spray studies, Knoche *et al.* (1998) showed that either decreasing droplet size and/or increasing carrier volume (at lower volumes) increased biological performance of 2,4-dichlorophenoxyacetic acid (2,4-D) and daminozide at a constant dose, but had little effect on the performance of GA₃. These data demonstrate that there is an optimum spray volume and droplet size that can maximize the biological activity of some growth regulators, but not others.

16.6.1 Drying rate (dew/rain/humidity/rewetting)

While a droplet is drying, there is an increasing rate of chemical concentration and an immediate uptake of the chemical, at least under laboratory conditions (Greene and Bukovac, 1971). When chemical solutions are almost dry, uptake of the remaining chemicals slows dramatically. If a surfactant is used, over 50% of NAA may be absorbed during the drying process, but the remaining chemical may be destroyed by light in 1–2 days. The hydration properties and/or decrease in pH of ammonium nitrate solutions with NAA may increase diffusion by increasing the number and mobility of the non-dissociated NAA species (Fader and Bukovac, 2001). Since carbaryl is not destroyed by light, it may remain unchanged on the leaf surface for a week or more, and rewetting by dew or a light rain may facilitate additional absorption.

Ethephon is pH-dependent and, as the droplet dries, the pH may increase or decrease, causing differences in evolution and absorption. After ethephon application, leaf ethylene evolution is very temperature-dependent and may be continuously evolved for more than a week at 21°C (Byers *et al.*, 2000b).

16.6.2 Effect of application temperature on chemical fruit thinning

Previous reviews suggest that chemical thinning increases with higher temperatures (Westwood, 1978; Williams, 1979). Jones and Koen (1985) showed a marked increase in fruit thinning by ethephon held in controlled-environment rooms as temperatures increased from 4 to 24°C. These trees were exposed to the specified temperatures 4 h prior to, during and after and held for 24 h.

In a laboratory experiment using pear cuticles, Greene and Bukovac (1971) showed substantial increases in penetration of NAD at increased temperatures. Edgerton and Haeseler (1959) reported similar results from NAA in a greenhouse study. Observations that thinning increased with higher field temperatures have been explained by greater chemical absorption at higher temperatures. D.W. Greene (Massachusetts, 1998, personal communication) has found little evidence for increased absorption of NAA with increased temperatures in the field, presumably because drying time decreased with lower humidity as temperatures increased. Jones *et al.* (1988) found no relationship between temperature and humidity with fruit thinning, but they found a linear decrease in thinning by NAA from 0800 to 2000 h. It is possible that the combined effect of a dark (night) period followed by a chemical thinning spray may explain the greater effect of the early-morning spray timing.

When NAA is used on most cultivars at cool temperatures, pygmy fruit that are in the 10–20 mm fruit size often remain on the tree, shrivel and die in the dormant season. These dead fruit frequently harbour rot organisms and increase inoculum the following season (K.S. Yoder and R.E. Byers, 1996, unpublished results). Though very controversial, early work indicated that temperatures of 13–29°C at the time of application did not affect thinning by NAA or NAD. In addition, when temperatures were cool, differences in chemical rate of 50% frequently gave no difference in thinning response (Thompson, 1957).

Little information exists on application temperature and its influence on thinning with hormone-type chemicals. In one field

experiment, applications of carbaryl at 2 h intervals from 0600 to 2000 h to 'Empire' / Mark trees caused similar thinning, even though application temperatures ranged from 18 to 36°C (R.E. Byers, 1996, unpublished results). In another field experiment, 'Starkrimson Delicious' / Mark trees sprayed with ethephon, Accell or carbaryl at 0600, 1400 or 2000 h caused similar thinning, even though temperatures were 14, 34 or 20°C, respectively; thus no strong relationship of temperature at application time with fruit thinning has been reported.

16.7 Influence of Photosynthetic Reserves on Fruit Set and Chemical Thinning of Apples Following Ovule Fertilization

In the spring when the temperatures have increased, photosynthetic reserves stored from the previous season are used to promote the first flush of growth and to retain fruit (Heinicke and Childers, 1937; Abbott, 1960, Hansen, 1971). During the period from bud break to approximately 30 days AFB, there is a net loss of organic carbon reserves. The greatest net deficit occurs about 20 days after flowering when fruit are about 12 mm in fruit diameter. This photosynthetic deficit corresponds to the time when trees are most sus-

ceptible to artificial or environmental fruit losses by shading (Byers *et al.*, 1991).

16.7.1 Effect of light and darkness on apple fruit retention and thinning

Apple trees grown in the eastern USA are typically exposed to 2–3-day periods of low light during cloudy/rainy periods. The low-light conditions can reduce photosynthetically active radiation (PAR) to 10–15% of full sun. Artificially shading trees (92% polypropylene shade material) for 2–3 consecutive days in the period of 14–28 days after bloom was found to reduce fruit set of spur 'Delicious' apple trees (Fig. 16.1). Under these shade conditions, the smallest fruit stopped growing before the larger fruit (Byers *et al.*, 1991; Fig. 16.2). In one test, if 1–2 days of sunlight separated each period of 2–3 days of artificial shade, much less fruit abscission occurred (Table 16.2). In addition, natural 'June' fruit drop appeared to be related to weather events that produced 2–3 days of intense cloudy weather at average temperatures above 16.7°C (Fig. 16.3; R.E. Byers *et al.*, 1991, 1998, unpublished results).

If we speculate that 10% PAR is required to maintain tree and fruit respiration during the daylight hours (the period from the hour after sunrise to the hour before sunset), the net

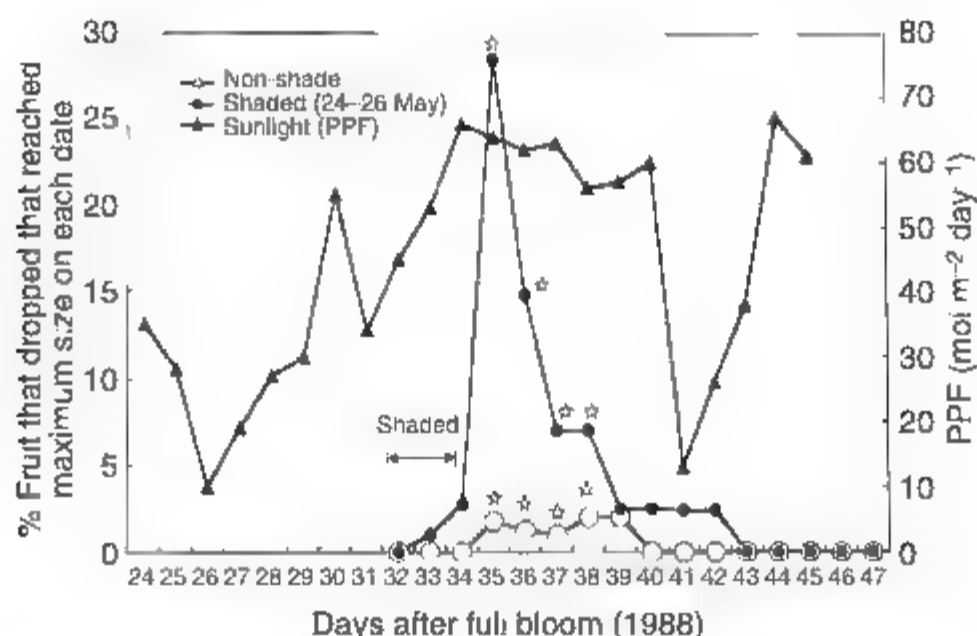


Fig. 16.1. 'Redchief Delicious' fruit diameter and daily photosynthetic photon flux (PPF) during May and June 1987. Shading trees for 3 days caused a high percentage of fruit to stop their growth on the 1st to 4th day after the period. A few larger fruit continued to grow for up to 8 days before stopping growth and later abscising.

†Statistical differences $P < 0.05$, for six trees (50 tagged fruit per tree measured daily) (From Byers *et al.*, 1991)

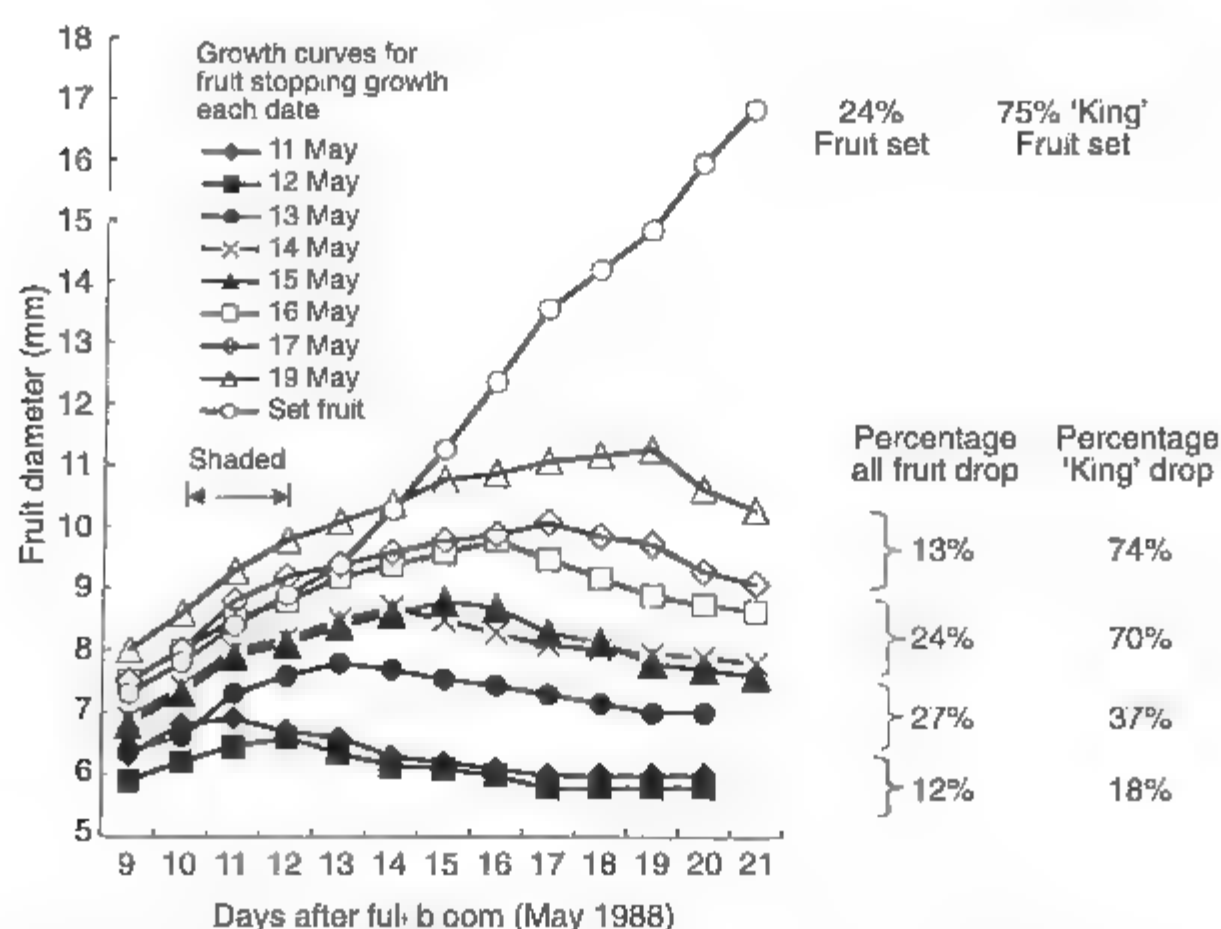


Fig. 16.2. Shading 'Redchief Delicious' trees for 3 days, 9 days AFB, caused 25% fruit drop of 'king' fruit and 75% of 'side' fruit to drop. The largest fruit destined to drop remained on the trees for more than 7 days after the end of the 3 days of shade (drop-induction period). The smallest fruit that dropped reached their maximum size during and soon after the shade event and remained on the tree for 7 days or more before abscising. (From R. E. Byers, 1988, unpublished results.)

Table 16.2. Effect of shade (92%) intervals on 'Campbell Redchief Delicious'/MM 111 apple tree fruit abscission (from Byers *et al.*, 1991)

Treatment ¹	Shaded days (days AFB)							Fruit per cm ² cross-sectional area of trunk (+ 56 days AFB)
	30	31	32	33	34	35	36	
Control								6.96 a ²
Shade			X	X	X			2.40 c
Shade + sun		X		X		X		4.29 b
Shade + sun		X	X					3.00 bc
Shade + sun		X		X				4.51 b
Shade + sun		X			X			6.11 a
Natural light levels (PPF mol m ⁻² day ⁻¹)	55	35	46	53	66	65	62	

¹ Full bloom occurred 22 April 1988. Shade treatments were started 31 days AFB when fruit were 20.3 mm ± 0.37 mm in diameter.

² Means of six trees. The control mean represented 857 fruit. Means separation within columns by Duncan's multiple range test, 5% level. PPF, photosynthetic photon flux.

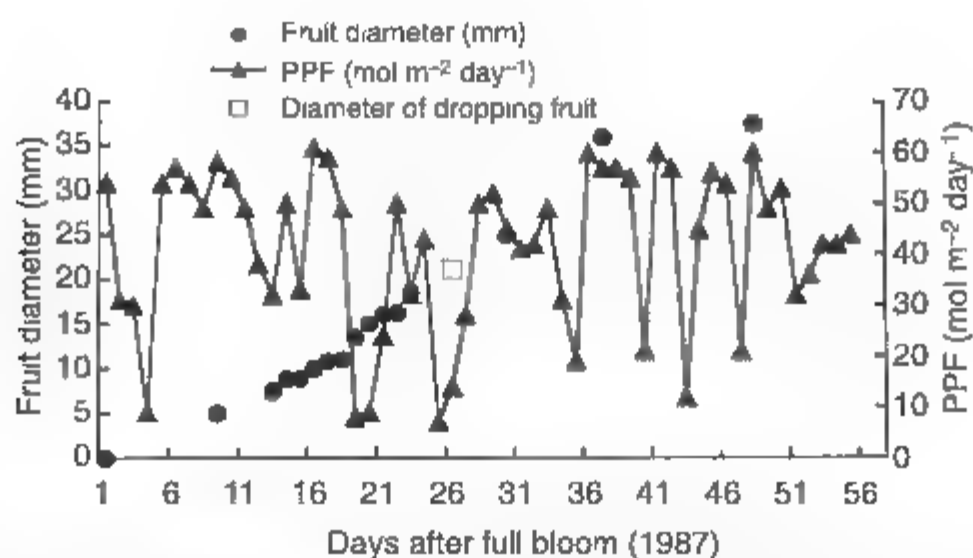


Fig. 16.3. 'Redchief Delicious' fruit diameter and daily photosynthetic photon flux (PPF) during May and June 1987. Fruit drop ('June drop') was initiated by naturally occurring low-light period(s). Near the end of a third major cloudy period (22–25 days AFB), average fruit diameter was 22–23 mm. Fruit dropping 38 days AFB were $21.4 \text{ mm} \pm 0.3 \text{ mm}$ (after reaching their maximum size, these fruit probably shrank by 1–2 mm). (From Byers *et al.*, 1991.)

photosynthetic needs of the tree may not be adequately met for the 24 h period. At night, no light-energy input occurs and all respiration is dependent on photosynthetic reserves accumulated in the day. During a typical dark/cloudy/rainy day, adequate photosynthesis may occur to meet the carbon demands during the day, regardless of the temperature or the light level. However, the period during darkness may cause a critical demand for photosynthates that are produced only during the day. The hours from 0800 to 1700 h, therefore, must provide the excess photosynthates required for the night period (approximately 15 h each day from 1700 to 0800 h); thus, the average night temperature, rather than the minimum temperature, may constitute a major influence on fruit retention each 24 h period.

In several field experiments where trees were sprayed with carbaryl (or NAA) on the first day of an artificial shade period, trees lost more fruit than if trees were not shaded (Byers *et al.*, 1971; Table 16.3). In addition, where artificially shaded trees were sprayed with carbaryl, less thinning occurred if 1 day of full sun was allowed after the shade period but before carbaryl was applied. In these studies, typically, 2 days of artificial shade induced more fruit drop than occurred following the application of the commonly used chemical thinners (carbaryl or NAA) (Byers *et al.*, 1991).

In three separate laboratory experiments, fruit retention was inversely related to temperature when trees (with fruit of approxi-

mately 10–15 mm diameter) were placed in controlled-environment rooms for 2–6 days in darkness. In one experiment, trees held at 4.4°C in darkness for 3 days did not lose fruit, whereas trees held at 21.1°C lost over 50% (Fig. 16.4; R.E. Byers, 2001, unpublished results). Thus, as light, darkness and temperature change after the application, the tree will become more or less susceptible to the absorbed thinner.

16.7.2 Effect of post-application temperature on chemical fruit thinning

Olien and Bukovac (1978) found that warm temperatures were required (approximately 10°C, or an activation energy of 30–32 kcal mol⁻¹) for ethephon to break down and release ethylene in detached cherry leaves. These data suggest that applications of ethephon made under cool conditions (i.e. below 10°C) may not result in adequate ethylene evolution to result in effective thinning. However, when potted trees grown in the field that were sprayed with ethephon were moved into controlled-environment rooms for 2 days, they were thinned equally well at 4.4 or at 21.1°C (R.E. Byers, 2001, unpublished results). Another group of potted trees did not give off ethylene from the ethephon spray when held at 4.4°C for 5 days but, when moved to another controlled-environment room at 21.1°C, ethylene was evolved at a level similar

Table 16.3. Effect of shade (92%) on chemical thinning of 'Campbell Redchief Delicious'/MM.111 apple trees (from Byers *et al.*, 1991)

Treatment ¹	Shaded days (S) Chemical thinners (T)							Fruit per cm ² cross-sectional area of limb (+ 56 days AFB)
	34	35	36	37	38	39	40	
Control (no shade)								7.93 a ²
Carbaryl + oil		T						4.34 b
Carbaryl + oil		ST	S					1.05 c
Carbaryl + oil		S	S	T				2.92 b
Carbaryl + oil		S	S		T			3.77 b
Shade		S	S					4.42 b
Natural light levels (PPF mol m ⁻² day ⁻¹)	66	65	62	62	56	57	60	

¹ Ful. bloom occurred 22 April 1988. Fruit size was 22.4 mm $\pm$ 0.35 mm on 27 May 1988 (35 days AFB).

² Means of six trees and the control mean represented 767 fruit. Means separation within columns by Duncan's multiple range test, 5% level.
PPF, photosynthetic photon flux.

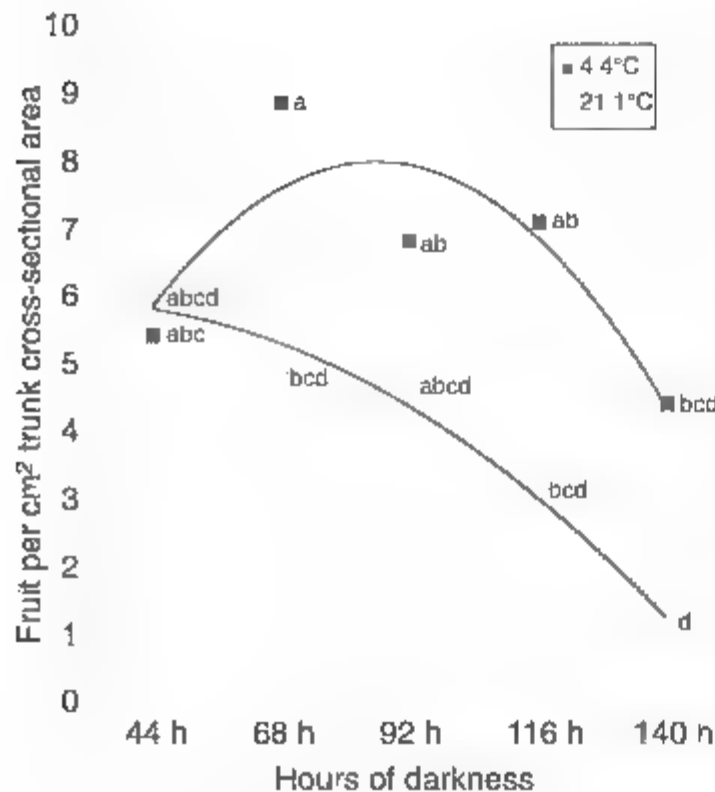


Fig. 16.4. Influence of continuous 44 to 140 h of darkness, or 125 h of 21 h darkness + 3 h sunlight each 24 h on fruit retention of 'Golden Delicious'/M 27 trees held in controlled environment rooms at 4.4°C or 21.1°C. Trees held in the dark from 68 to 140 h at 4.4°C maintained more fruit than those held at 21.1°C. Trees held for 68 or more h at 21.1°C lost more fruit than trees held at 4.4°C. Letters indicate mean separation by Duncan's multiple range test, 5% level. (From R.E. Byers, 2001, unpublished results.)

to those constantly held at 21.1°C. These data suggest that the response from ethephon thinning sprays is largely controlled by the plant metabolic status in response to changing environmental temperatures.

Personal observations of chemical thinning by growers have led me to believe that the combination of chemical thinner, low light and warm night temperatures frequently causes serious overthinning, whereas the combination of thinners applied under low light plus cool conditions causes much less thinning and an increase in the proportion of undersized and pygmy fruit. In addition, natural 'June drop' appears to be triggered by a low leaf-to-fruit ratio in periods of low light plus warm temperatures (Byers *et al.*, 1991), but, if temperatures are cool, little 'June drop' may occur.

These results also raise the question about the effectiveness of carbaryl, NAA and 6-BA when temperatures are cold (4.4°C). Theoretically, if a chemical thinner has been absorbed, it may be present in the tissue and a critical level of metabolism (driven by temperature) may be required for the plant to respond to absorbed chemicals. Cool temperatures may delay or interfere with action and increasing temperatures may promote abscission.

16.7.3 Physiological vs. temperature basis for timing chemical applications

Much emphasis has been placed on determining the maximum effectiveness for each chemical thinner based on the diameter of the developing fruit. For NAA, the maximum sensitivity period for abscission has varied considerably in several reports while in others there has been no apparent relationship over the period from petal fall (PF) to about 15 mm fruit diameter (i.e. PF to about 25 days AFB) (Donoho, 1968; Leuty, 1973; Marini, 1996). Carbaryl also appeared to have a wide range of effective thinning times, ranging from PF to about 20 mm fruit diameter (i.e. PF to 30 days AFB). Furthermore, ethephon may cause fruit abscission from PF to 30 mm fruit diameter (i.e. PF to 40 days AFB) (R.E. Byers, 2001, unpublished results). Fluctuating temperatures during the post-thinning period have seldom been the focus of field experiments. Many of the early timing studies could have been confounded by post-temperature and sunlight levels, which were seldom reported. Donoho (1968), who reported light, temperature and humidity, suggested two periods of maximum sensitivity for NAA. However, these trees may have been more susceptible to thinning since the two maximum-sensitivity periods also correlated with two low-light periods.

Regression analysis of 20 years of thinning trials on five spur 'Delicious' strains using 50 different spray treatments indicated that higher night temperatures were more highly correlated to chemical thinning ($r^2 = 0.19$; $r^2 = 0.21$) than daytime temperatures ($r^2 = 0.12$; $r^2 = 0.11$) or the average of the day and nighttime temperatures ($r^2 = 0.16$) (Byers *et al.*, 2000a). Even though the regression coefficients were low, they were highly significant. In these data sets, chemical thinning was not significantly correlated with days AFB or fruit diameter; however, a ranking of spray treatments by various chemical combinations chosen for degree of expected thinning ($r^2 = 0.71$) was highly significant. In addition, a ranking of the 'Delicious' strains by ease of thinning was also highly significant ($r^2 = 0.15$).

16.7.4 Temperature probabilities for thinning

An analysis of temperatures in Winchester, Virginia, from 1984 to 1993, showed that during the 3-week period from 0 to 21 days AFB, the maximum temperatures for 3 days or more reached above 29.5°C in 7 out of 10 years. In the 1-week period from 15 to 21 days AFB (typically considered the optimum thinning period at 8–12 mm fruit diameter), 3 or more days of temperatures above 29.5°C occurred in only 3 out of 10 years. To obtain the same degree of probability for the 3-week period (7 out of 10 years) as for the 1-week period, the temperature would have to be dropped by 5.5°C to 24°C. Since the fruit diameter, Julian date or days AFB were not found to be important factors (Byers *et al.*, 2000a), the data suggest that thinning should be based on temperature considerations in the 3-week period, not fruit diameter or days AFB. In this analysis, the chemical combination chosen for thinning was the most important factor, followed by temperature and, thirdly, the strain of 'Delicious'. Unfortunately, light levels were not readily available for the data for these experiments, and a host of other influential factors may have been significant, but none were presumed to be of primary importance.

16.7.5 Pruning and mechanical fruit thinning

Dormant pruning reduces the number of flower and vegetative buds, resulting in a greater supply of organic carbon reserves for fruit set and fruit growth for the remaining vegetative and floral buds. Pruning may easily remove 30–80% of the flower buds before growth has started in the spring. In addition, pruning restricts tree height and spread, reduces canopy density, increases spray penetration, helps maintain tree structure, promotes regular bearing, stimulates shoot growth, inhibits flower-bud formation but increases spur vigour and flower-bud size, increases the percentage of flowers setting fruit, improves fruit size, quality and colour and results in a reduction of the current

season's yield but may promote yields of the most valuable fruit sizes over the 2-year bearing cycle (Mika, 1986). Forsythe (1802, reviewed by Davis, 1957) made detailed recommendations for pruning and training systems designed to 'keep trees in a constant state of bearing, which if left to nature would produce a crop only once in two or three years'. Roberts (1952) showed that fruit set, fruit size, leaf size, shoot length and the subsequent season's return bloom could be substantially increased by detailed removal of 70% of the growing points by heading cuts in the dormant season, even after flower-bud size had been determined. He demonstrated that heavy pruning in the 'on year' could decrease the number of flower buds and stimulate growth and flowering in the 'off year'.

Mechanical methods of fruit (or flower) removal have the advantage that the number and distribution of fruit remaining on the tree can be visually observed during the thinning process. Mechanical shakers used

for thinning apple and pear fruit were found to be non-selective for apple fruit size, and the trees must be pruned to have stiff branches. Mechanical thinning has been found to be effective only for short, non-flexible peduncles, which are produced only on a few cultivars at about 60 days AFB. No improvement in return bloom was found. Late hand-thinning or late chemical thinning would be expected to increase fruit size due to removal of smaller fruit.

16.8 Chemicals that Induce Flower-bud Formation Without Thinning

When biennial-bearing cultivars flower heavily and carry a full crop, early thinning may not provide an adequate return bloom for a return crop in the next season. During the thinning period, multiple applications at low rates of ethephon have been used to promote return bloom of apple, while avoiding

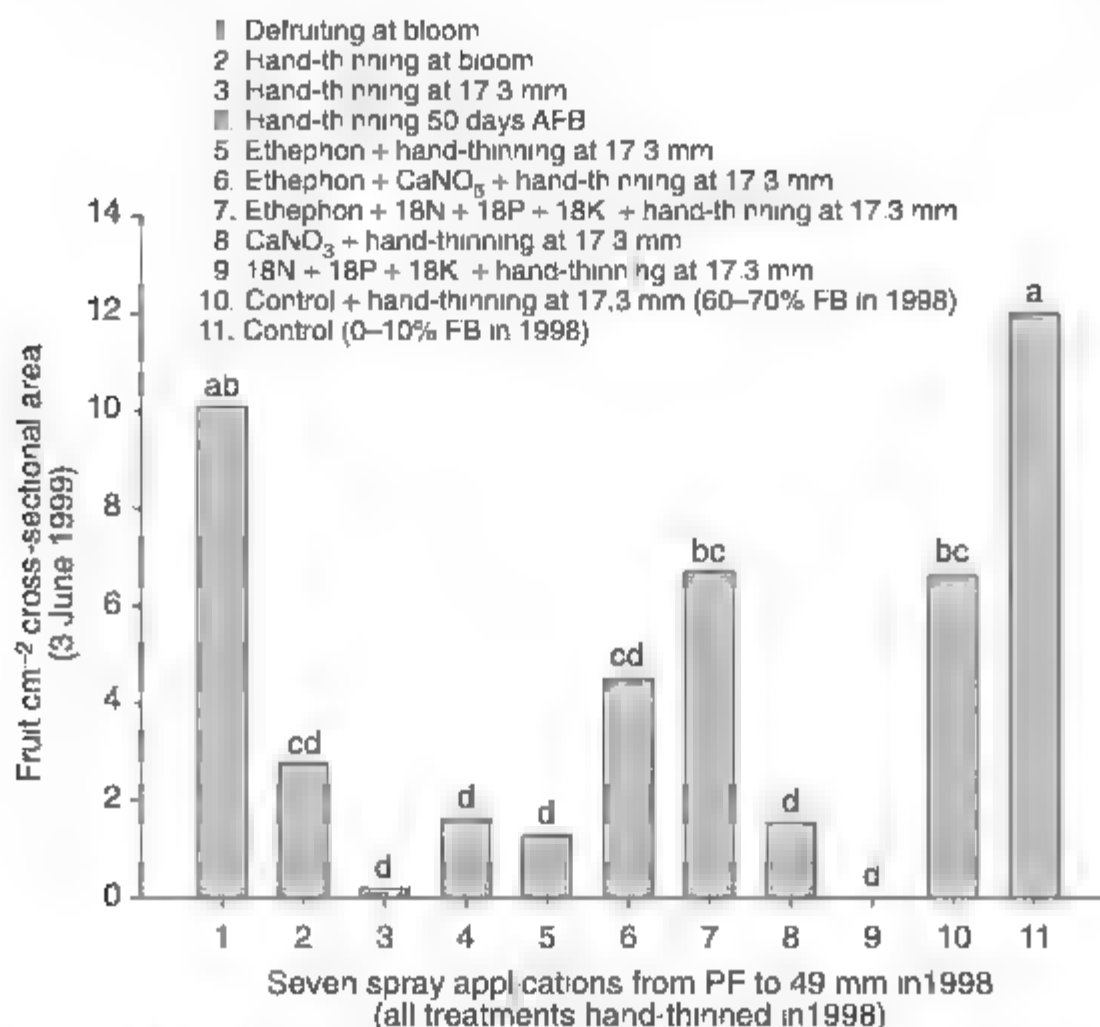


Fig. 16.5. The combination of ethephon plus a nitrogenous foliar spray in the spring of 1998 (seven weekly applications, provided adequate return bloom for a full crop in 1999 (treatment Nos 6, 7) 'York'/M.27 trees were selected for 90% or more of the spurs flowering. Trees with 60% spurs flowering or 10% spurs flowering (treatment Nos 10, 11), also had an adequate return bloom for a full crop in 1999. Letters indicate mean separation by Duncan's multiple range test, 5% level. (From Byers *et al.*, 2000b)

fruit abscission from higher rates (Byers, 1993). In one study when trees were heavily loaded, neither ethephon nor a foliar nutrient spray alone promoted flower-bud formation, but the combination of the two greatly promoted return bloom and fruit set (Byers *et al.*, 2000b; Fig. 16.5). There is some evidence that NAA may directly promote flower-bud formation (Harley *et al.*, 1958) and it has occasionally been used commercially for that purpose.

16.9 Conclusion

The economic impact of thinning on crop value is comprised of the yield and prices of the most valuable fruit size categories averaged over two or more years. Early fruit or bloom thinning has not always achieved the desired fruit size, return bloom, and/or annual bearing, particularly of strongly biennial bearing cultivars. Even though consider-

able progress has been made to increase crop value by early flower and fruit thinning, continued efforts will be needed to develop as new cultivars, rootstocks and training systems evolve.

To maximize crop value, future strategies may include: (i) pre-conditioning chemical spray(s) to make trees more responsive to thinning chemicals; (ii) combinations of chemicals with different modes of action (photosynthetic inhibitors, auxin transport inhibitors, flower bud inhibition or stimulation, adjuvants, pruning and other cultural practices) that lead to consistent and reliable cropping; (iii) accurate and continuous computerized information on tree physiological condition (or carbon balance) and their interactions with important environmental fluctuations that influence natural fruit retention/abscission and chemical response(s); and (iv) chemical application strategies to removal of smaller unwanted or pygmy fruit.

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1.2.



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1.4.



1.5.



Plate 1.1. *Malus sieversii* is a predominant overstorey species in the forests of eastern Kazakhstan

Plate 1.2. Morphological variation among fruit collected in eastern Kazakhstan from trees of *Malus sieversii*.

Plate 1.3. Several species of *Malus* are frequently used as ornamental trees. Here different crab apple selections make an attractive avenue.

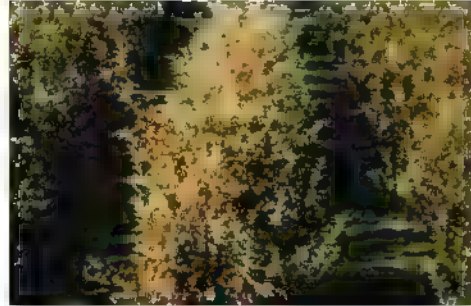
Plate 1.4. A selection of over 50 older apple cultivars. Included in those shown are 'Glory of England', 'Grimes Golden', 'Lady Hamilton', 'Nonpareil', 'Rhode Island Greening' and 'Winter Banana'.

Plate 1.5. Very high-density (over 4000 trees ha⁻¹) super-spindle apple trees growing near Bolzano in the Alto Adige region of northern Italy. Nursery stock is being grown between the rows

1.6.



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Plate 1.6. High-density slender-spindle apple trees, typically planted with 3.0–3.5 m between rows and 1.0–1.25 m within the rows, growing in The Netherlands.

Plate 1.7. Semi-intensive 'Royal Gala' apples, trained as centre-leader trees and typically grown with 5 m x 3 m spacings, in Hawke's Bay, New Zealand. Moderate year-round conditions, high sunshine hours and deep fertile soils make this one of the most productive apple-producing regions of the world.

Plate 1.8. Semi-intensive centre-leader-trained apple trees growing near Grabouw in South Africa. Hot summer conditions and mild winters allow the commercial production of both apples (foreground) and citrus (background) in the same area.

Plate 1.9. Large 'Rome Beauty' trees on seedling rootstock, planted with 7.5 m x 7.5 m spacings in Ohio, exemplify older plantings in the USA.

Plate 1.10. Extensive apple plantings, primarily of 'Red Delicious', trained as centre-leader trees, in Washington State, USA. High summer and cold winter temperatures typify the growing conditions in this arid, continental region.

1.11.



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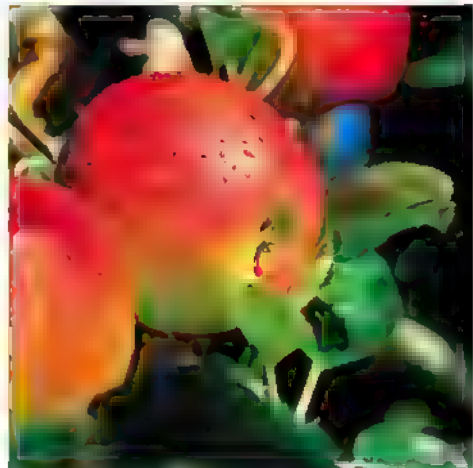


Plate 1.11. Production in China, now the world's largest producer of apples (20 million t in 2001). These 5-year-old 'Fuji' trees on *Malus prunifolia* rootstock, are planted at 4 m x 3 m spacing. Vegetables are being cultivated between the rows.

Plate 3.1. Modern breeding programmes generate many hundreds of progeny from each cross between selected parents. Large land areas are needed to accommodate the seedling populations, which, because of the need to grow through a juvenile phase, may need to be maintained for several years before the onset of flowering and the initial evaluation of potential value

Plate 3.2. Progeny arising from one cross can produce a very diverse range of fruit types – including different sizes, colours and shapes.

Plate 3.3. 'Pacific Rose'

Plate 3.4. 'Sci' fresh apples now being marketed as 'Jazz'.

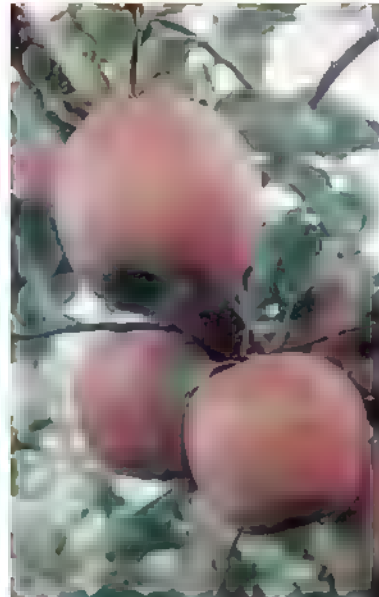
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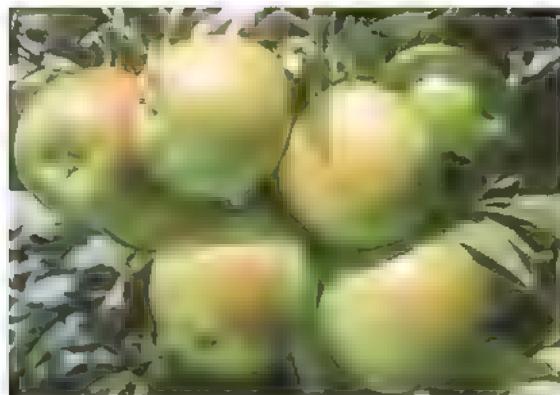


Plate 3.5. Colour sports of 'Gala' developed naturally as mutations.

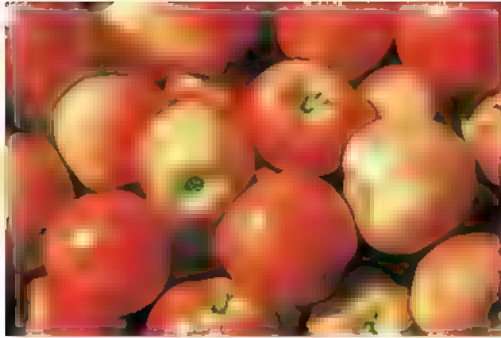
Plate 4.1. 'Delicious', unspecified red strain (from Bruce Barritt)

Plate 4.2. 'Golden Delicious', Reinders strain (from Praktijkonderzoek Plant and Omgeving, The Netherlands).

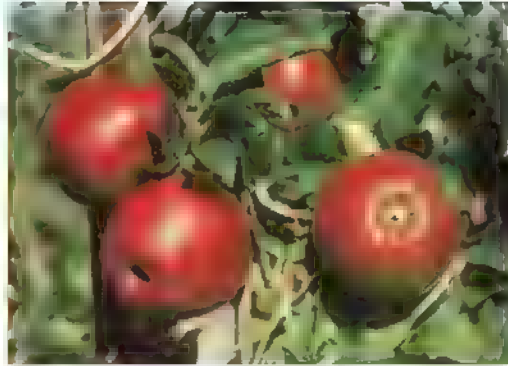
Plate 4.3. 'Fuji' (from Agriculture and Agri-Food Canada)

Plate 4.4. 'Granny Smith' (from Bruce Barritt)

4.5.



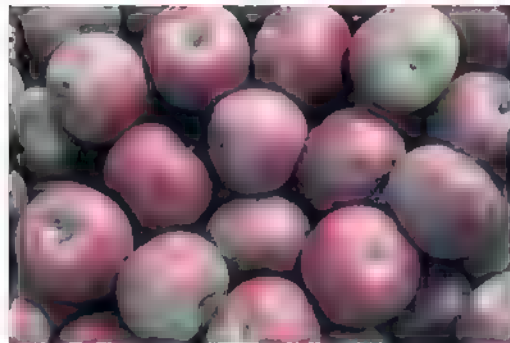
4.6.



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Plate 4.5. 'Imperial Gala' (from Bruce Barritt)

Plate 4.6. 'Jonathan' (from Praktijkonderzoek Plant and Omgeving, The Netherlands).

Plate 4.7. 'Jonagold' (from Praktijkonderzoek Plant and Omgeving, The Netherlands).

Plate 4.8. 'McIntosh' (from Bruce Barritt)

Plate 4.9. 'Rome Beauty', unspecified red strain (from Agriculture and Agri-Food Canada)

4.10.



4.11



5.2.



4.12.



5.1.



Plate 4.10. 'Braeburn' (from Praktijkonderzoek Plant and Omgeving, The Netherlands)

Plate 4.11. 'Elstar' (from Bruce Barritt)

Plate 4.12. 'Cox's Orange Pippin' (from Bruce Barritt)

Plate 5.1. Bed system of apple scions growing on M.27 rootstock in the UK.

Plate 5.2. A typical three-row bed system of 'Queen Cox' apples planted on M.9 EMLA rootstocks in the UK.

5.3.



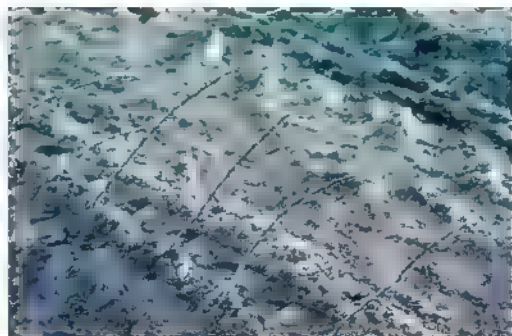
6.3.



5.4.



6.1.



6.2.



Plate 5.3. Two-row system of seventh-leaf 'Granny Smith' on M.26 rootstock in the USA.

Plate 5.4. Traditional vigorous 40-year-old trees of the cultivar 'Early Victoria' on seedling rootstocks.

Plate 6.1. Obliquely planted M 9 liners as starting material for a new layer bed.

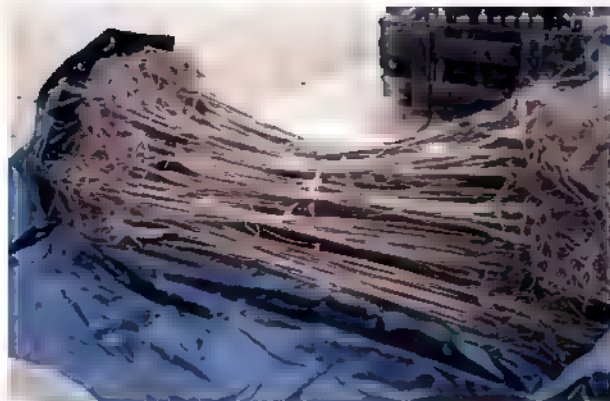
Plate 6.2. Example of a machine for harvesting rooted plants from a layer bed.

Plate 6.3. Layer bed of M 9: at the right, first season: at the left, second season

6.4.



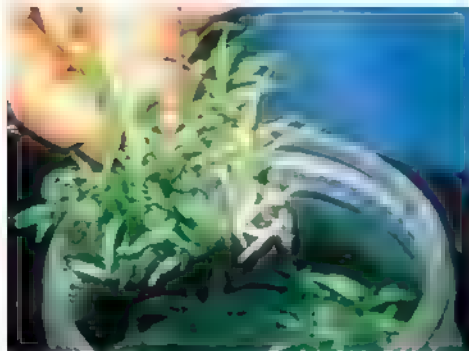
6.5.



6.6.



6.7.



6.8.



Plate 6.4. Mature layer bed of M.9.

Plate 6.5. Bundles of rootstock hardwood cuttings harvested after bedding for 1 year in the nursery.

Plate 6.6. Hard-pruned hedges of apple rootstocks.

Plate 6.7. *In vitro* micropropagated apple shoots prior to subculturing

Plate 6.8. 'Starkspur Golden Delicious', rooted *in vitro*.

6.9.



6.11.



6.10.



6.12.



6.13.

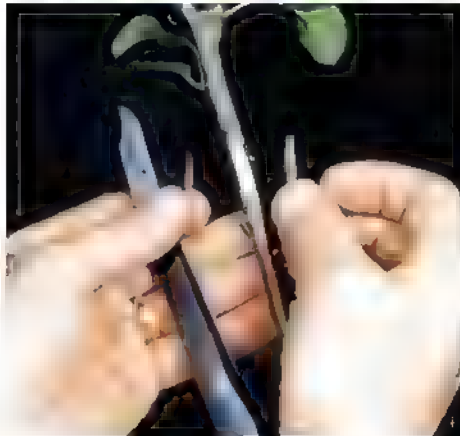


Plate 6.9. Ex-micropropagated 'Starkspur Golden Delicious' in the orchard 4 years after being planted as a small whip. Note the lack of fruits

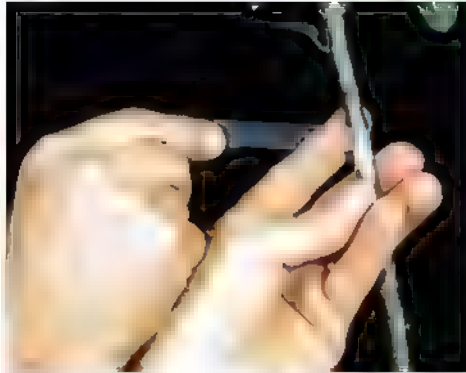
Plate 6.10. One-year-old trees of 'Red Boskoop' on M 9. Trees from left to right: unsprayed, or sprayed eight times (weekly) with 50, 100, 300 or 600 p.p.m. benzyladenine, respectively, to improve feathering

Plate 6.11. 'Snip' tree of 'Elstar' on M 9. Tree made from a table graft and cut back at 50 cm after the first nursery year

Plate 6.12. Productive interstem tree of 'Elstar' on M 9 in the second leaf in the orchard.

Plate 6.13. Chip budding.

6.14.



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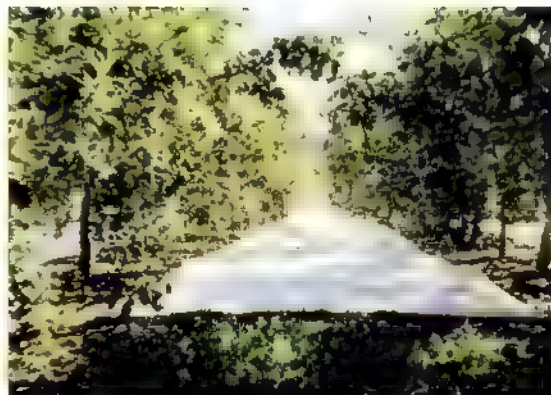


Plate 6.14. Tying the chip to the rootstock.

Plate 8.1. Detailed monitoring of soil-moisture status and tree transpiration rates in experimental systems improves knowledge of apple tree water use. Enhanced water-use efficiency through better irrigation scheduling can result from such studies.

Plate 9.1. Whole-tree gas-exchange chambers used for determining photosynthesis rates of intact apple canopies. Impacts of factors such as water stress and crop load can be assessed through using such sophisticated equipment.

Plate 9.2. Fish-eye photograph used to assess canopy openness and light penetration as influenced by training system or pruning.

Plate 9.3. Reflective mulch used under 'Fuji' trees to improve fruit colour.

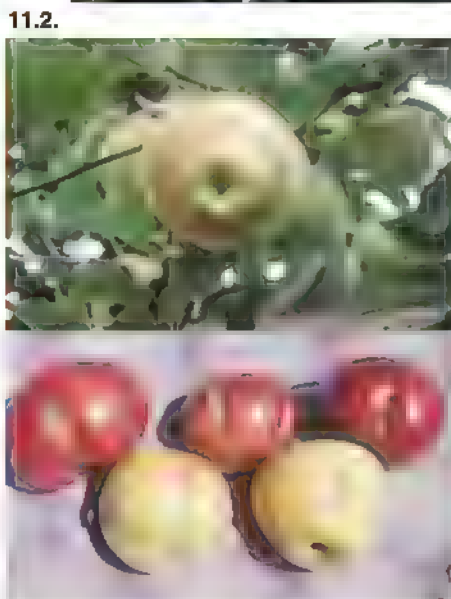
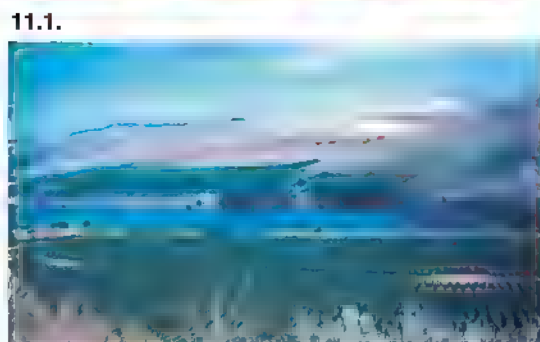
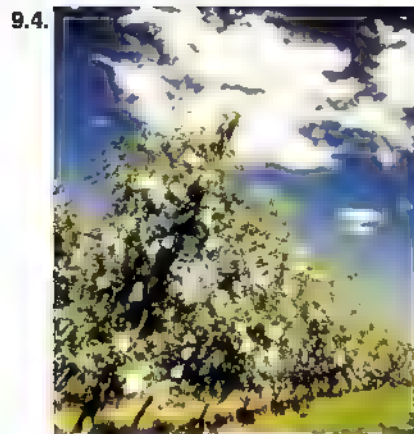


Plate 9.4. 'Fuji' trees with paper bags around individual fruit to enhance colour when bags are removed (from Bruce Barritt).

Plate 9.5. 'Fuji' apples previously bagged with stems clipped and ready for market. Bagging normally enhances value as fruit are sold individually (from Bruce Barritt).

Plate 10.1. Large controlled environment rooms being used to study the impacts of temperature on apple fruit growth rates at different times throughout the growing season.

Plate 11.1. Orchard in Washington State, USA, planted close to a lake to reduce risk of spring frost and as a water-supply.

Plate 11.2. Top. 'Frost ring' on 'Gala' apple resulting from cold injury to the surface cells within a few days following full bloom. The injured cells callused, giving the surface a russeted appearance. Bottom. 'Delicious' and 'Golden Delicious' apples in which the outer flesh were frozen approximately 3 weeks after full bloom. The skin split but the cracks callused and healed. In neither case were the temperatures sufficiently cold for a long enough period to freeze the developing seeds; therefore the fruit matured, although severely damaged by the cold.

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12.2.



Plate 11.3. Orchard in British Columbia, Canada, planted across a hillside.

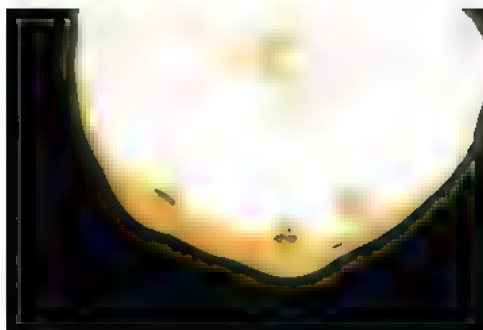
Plate 11.4. Orchard planted on the contour of the hillside

Plate 11.5. Young trees in British Columbia, Canada, in a modern orchard trained to the axis system.

Plate 12.1. Leaf symptoms of potassium deficiency on 'McIntosh'.

Plate 12.2. Leaf symptoms of magnesium deficiency.

12.3.



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12.7.



12.6.

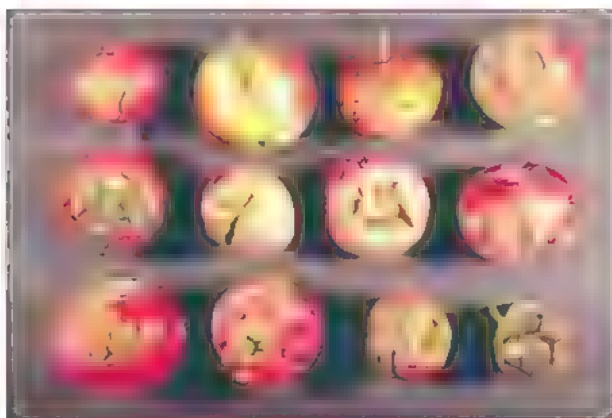


Plate 12.3. Bitter pit – a calcium deficiency disorder – as manifested in 'Golden Delicious' apple

Plate 12.4. Internal breakdown of 'Spartan' caused by calcium deficiency.

Plate 12.5. Boron deficiency in apple as manifested by drying and shrivelling of blossom.

Plate 12.6. Boron deficiency causing surface cracking of fruit.

Plate 12.7. Boron toxicity on 'Golden Delicious'.

12.8.



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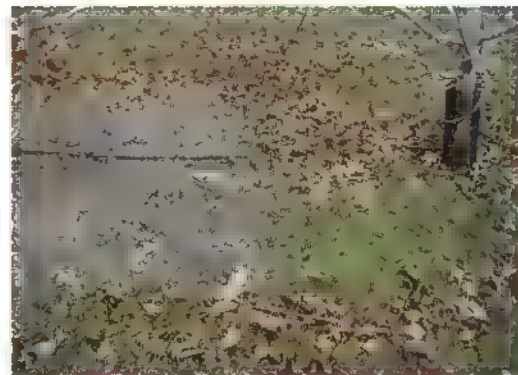


Plate 12.8. Zinc-deficiency symptoms manifested on young 'Delicious'/M.9 apple trees.

Plate 12.9. Iron deficiency.

Plate 12.10. Manganese deficiency.

Plate 13.1. Colour and size differences of fruit from trees growing in mowed sod grass (right) compared with bare-soil residual-herbicide treatments (left), on the same harvest date for 'Jonagold' apples in a New York orchard. Cumulative fruit yields (1989–1994) were about 25% lower in the sod-grass treatment, but fruit quality and market value were consistently higher in sod than in the herbicide treatment (from Merwin and Stiles, 1994).

Plate 13.2. Soil-surface and ground-cover-vegetation conditions beneath trees during early December 2000, in contiguous orchard-floor management (OFM) plots after 8 years of treatments with pre-emergence herbicides (bare soil on left) versus a post-emergence herbicide (moss- and weed-covered soil on right) in a New York orchard. Despite the substantial 'weed' ground cover during dormant seasons in the post-emergence herbicide treatment, cumulative yields (1994–2000) were greater in this OFM system compared with bare-soil residual herbicides. Note that weathering has eroded the upper 1 cm topsoil of fine soil particles, exposing a gravelly layer in the residual-herbicide treatment (from an ongoing study described in Merwin *et al.*, 1996).



13.3.



13.4.



14.1.

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Plate 13.3. A front-mounted shielded-boom herbicide sprayer (Phil Brown Welding Co., Conklin, Michigan, USA) for applications within the tree row. Metal or plastic shielding above nozzles reduces drift and spray damage to tree trunks and foliage, facilitating herbicide application under moderately windy conditions

Plate 13.4. Orchard mowers with low vertical profiles and adjustable side-wings permit close and effective mowing of various alley widths and within tree rows without damage to low hanging branches laden with fruit around harvest time (mower shown is Perfect™ model DR365, as manufactured by Van Wamel, BV, BenedenLeeuwen, The Netherlands)

Plate 13.5. Top and bottom: views of a prototype shrouded propane flame weeder developed by I. Merwin, J. Ray and K. Bittner at Cornell University, for weed suppression beneath trees and vines. The unit floats on two ground skids, with dual torches facing forward beneath a protective metal shroud, which reduces fuel consumption and minimizes heat damage to trees, vines and trickle-irrigation lines

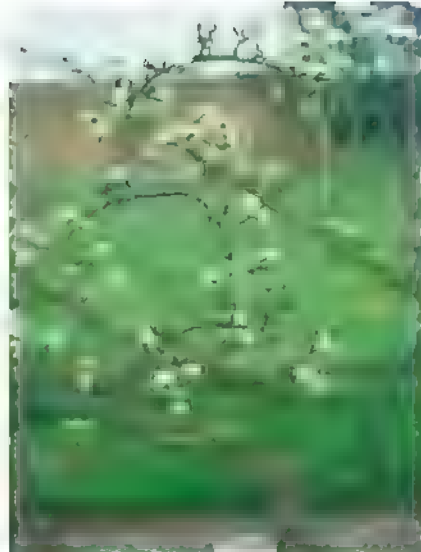
Plate 14.1. Large apple trees on seedling rootstock with minimal pruning and training.

Plate 14.2. Unpruned (left) and summer-pruned container-grown apple trees showing the reduction in shoot growth, leaf size and root growth (from Taylor and Ferree, 1981)

14.3.



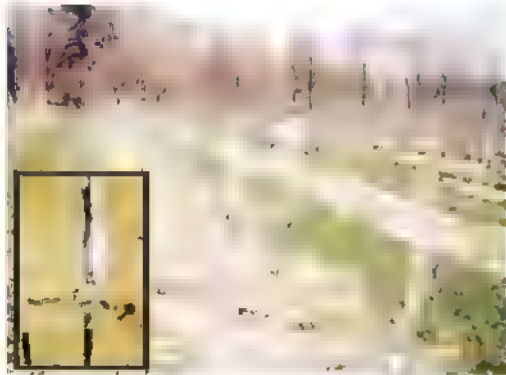
14.4.



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15.1.



Plate 14.3. Mechanical root pruning of apple trees at bloom

Plate 14.4. Apple tree trained in an ornamental form using bending and pruning

Plate 14.5. Chain-saw cut used to interrupt phloem transport and reduce apple tree growth (from Steve Hoying)

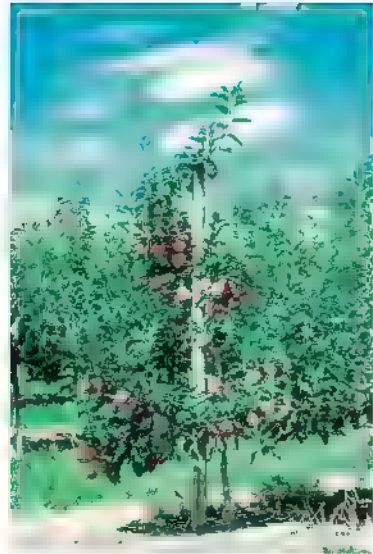
Plate 14.6. Plastic sleeves used to induce bud break on vigorous young apple trees (from Steve Hoying).

Plate 15.1. Traditional globe-shaped apple tree of 'McIntosh' on seedling rootstock.

15.2.



15.3.



15.4.



15.6.



15.5.



Plate 15.2. Central-leader apple tree of 'Gala' on MM.106 rootstock with four distinct tiers of branches.

Plate 15.3. Slender-spindle apple tree of 'Gala' on M.9 rootstock with leader zigzagging to limit tree height (from Bruce Barritt).

Plate 15.4. Vertical-axis apple trees of 'Gala' on M.9 rootstock (from Bruce Barritt)

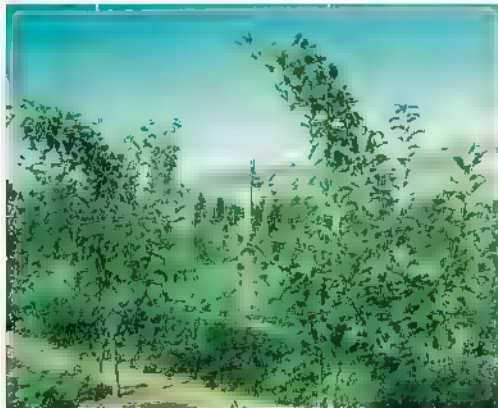
Plate 15.5. Vertical-axis apple orchard of 'Golden Delicious' on M.9 rootstock. Upper arrow denotes large branch to be removed back to an angled stub. Lower arrow denotes renewal branch arising from the stub of a previous year's pruning cut.

Plate 15.6. Solaxe apple tree of 'Jonagold' on M.9 rootstock with lower branches bent down in a pendant position

15.7.



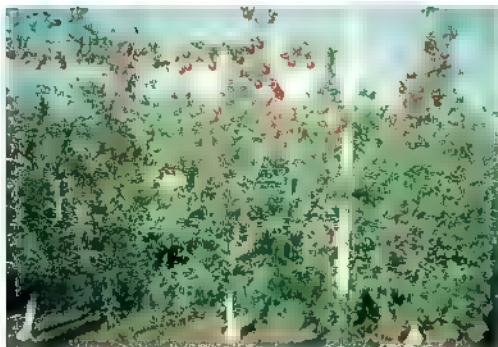
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15.11.



Plate 15.7. Slender-pyramidal apple tree of 'Gala' on M.26 rootstock with distinct tiers of horizontal branches.

Plate 15.8. HYTEC apple trees of 'Gala' on M.9 rootstock with the central leader tied over at a 45° angle to reduce the vigour of the top.

Plate 15.9. Super-spindle apple orchard of 'Empire' on M.9 rootstock.

Plate 15.10. Horizontal-palmette-trellis tree of 'Jonagold' on M.26 rootstock.

Plate 15.11. Lincoln-canopy apple orchard of 'Delicious' on MM.106 rootstock with vigorous shoot growth arising from the horizontal canopy.

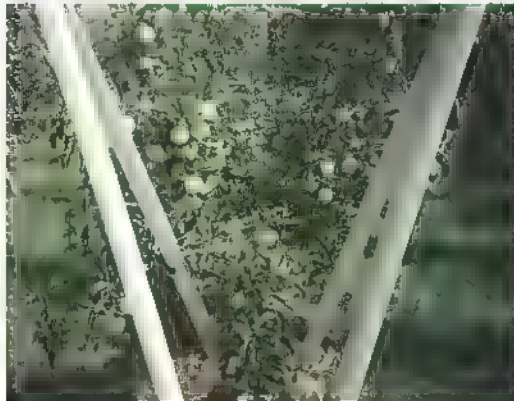
15.12.



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16.1.



Plate 15.12. Geneva Y-trellis apple orchard of 'Empire' on M.26 rootstock.

Plate 15.13. MIA trellis (A-shaped trellis) apple orchard of 'Gala' on MM 106 rootstock.

Plate 15.14. Gütingen V-slender-spindle apple orchard of 'Jonagold' on M 9 rootstock.

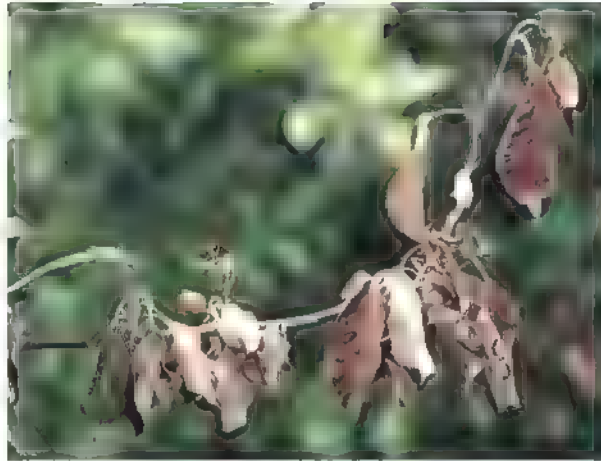
Plate 15.15. V-super-spindle apple orchard of 'Gala' on M 9 rootstock.

Plate 16.1. 'Redchief Delicious' apple injury caused by Carbaryl + Accel + Regulaid under certain environmental conditions: (A) 2 weeks after treatment; (B) near harvest; and (C) at harvest (from Byers *et al.*, 2000a).

18.1.



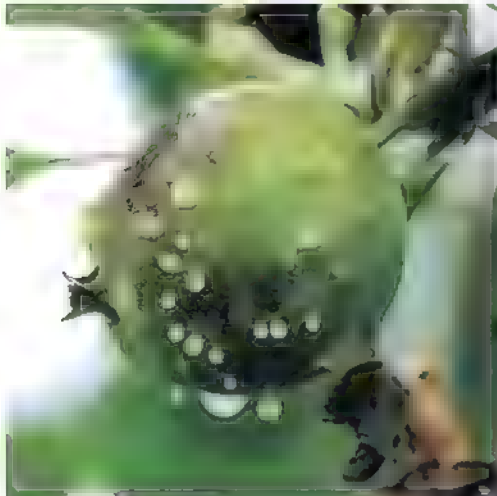
18.2.



18.4.



18.3.



18.5.



Plate 18.1. Dieback of apple spurs and shoots caused by fire blight, the disease caused by the bacterium *Erwinia amylovora* (from A. L. Jones)

Plate 18.2. Apple spur and shoot with fire blight. Infected foliage appears scorched. The 'shepherd's crook' recurving of the shoot tip is a diagnostic symptom of the disease (from A. L. Jones).

Plate 18.3. Apple fruit with fire blight, note ooze (from A. L. Jones)

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Plate 18.5. Symptoms of apple scab on immature 'McIntosh' fruit (from A. L. Jones)

18.6.



18.7.



18.8.



18.9.



18.10.



Plate 18.6. Foliar/shoot symptoms of powdery mildew, caused by *Podosphaera leucotricha* (from A. L. Jones).

Plate 18.7. Net-russet symptoms of powdery mildew on infected apple fruit (from A. L. Jones)

Plate 18.8. European brown rot on apple fruit (from A. L. Jones)

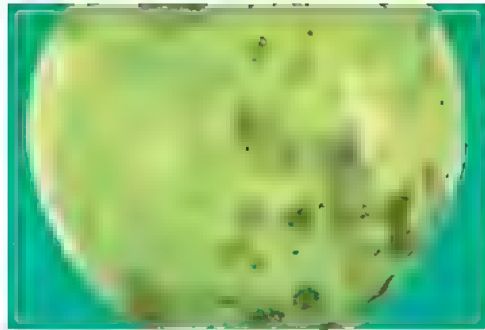
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Plate 18.10. Cortland apples with black rot; one is mummified with pycnidia. The disease is caused by *Botryosphaera obtusa* (from A. L. Jones)

18.11.



18.12.



18.13.



18.14.



18.15.

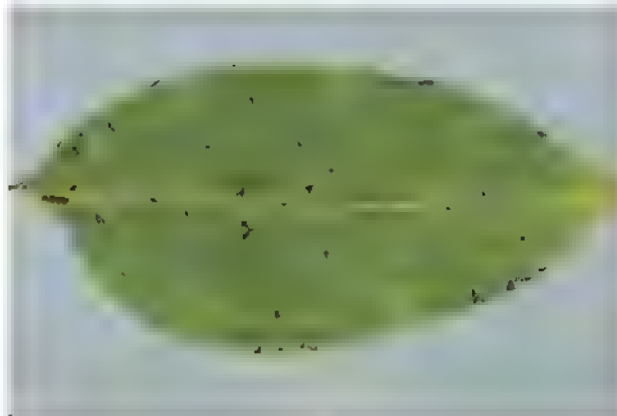


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Plate 18.12. Sooty blotch and a few fly-speck lesions on apple (from A.L. Jones).

Plate 18.13. Black, shiny fly-speck lesions on apple, caused by *Schizothynnium pomi*. Sooty blotch is evident above fly-speck lesions (from A.L. Jones).

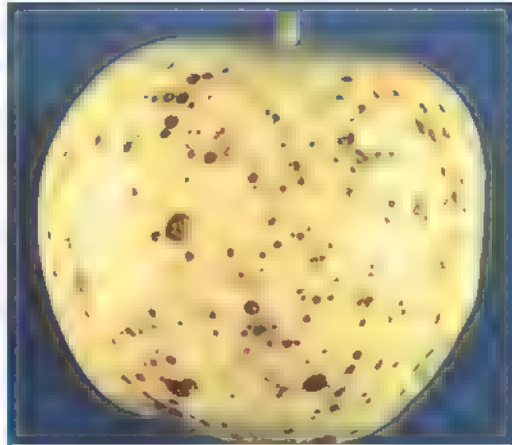
Plate 18.14. Brooks spot at the calyx end of 'Grimes Golden' apple, caused by *Mycosphaerella pomi* (from A.L. Jones)

Plate 18.15. Purple spots on apple leaf caused by Brooks spot (from A.L. Jones)

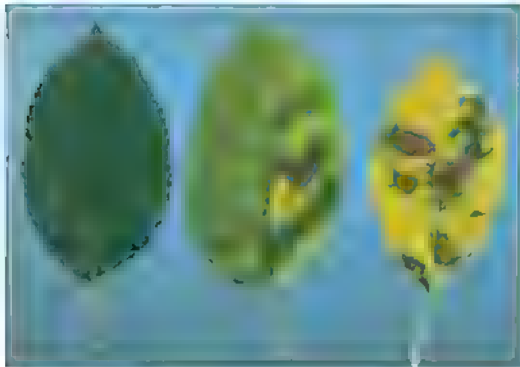
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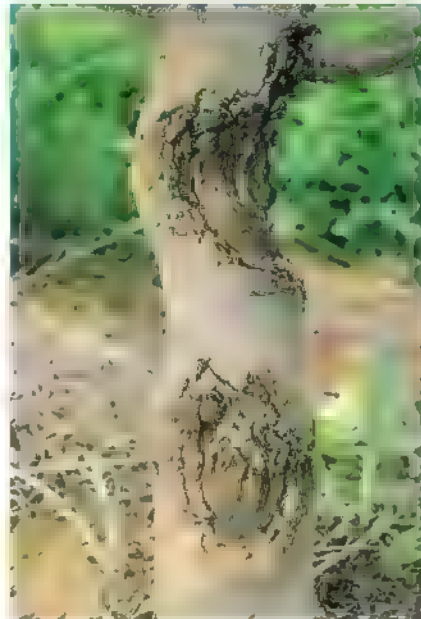
18.17.



18.18.



18.20.



18.19.



Plate 18.16. *Alternaria* blotch on leaves of 'Delicious', caused by *Alternaria mali* (from A. L. Jones).

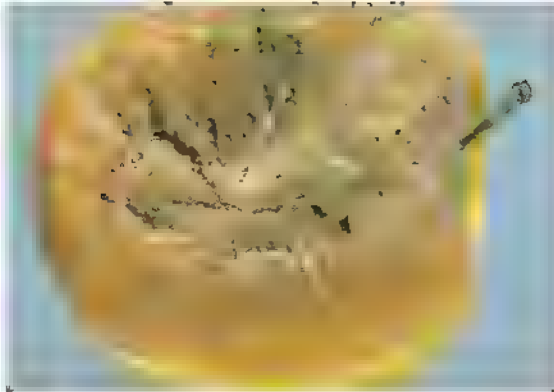
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Plate 18.18. Necrotic leaf blotch, a physiological disorder, on cultivar 'Golden Delicious' (from A. L. Jones).

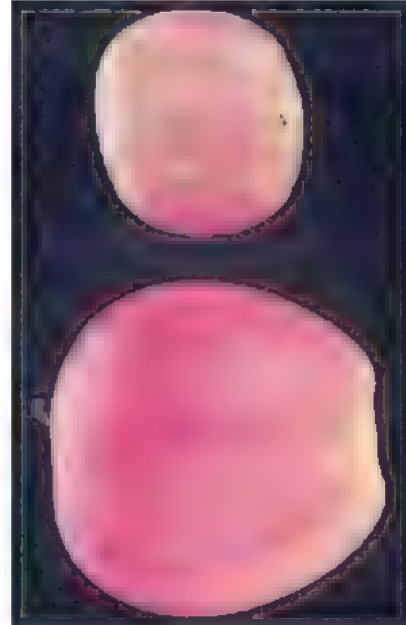
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18.21.



18.22.



18.24.



18.23.



18.25.

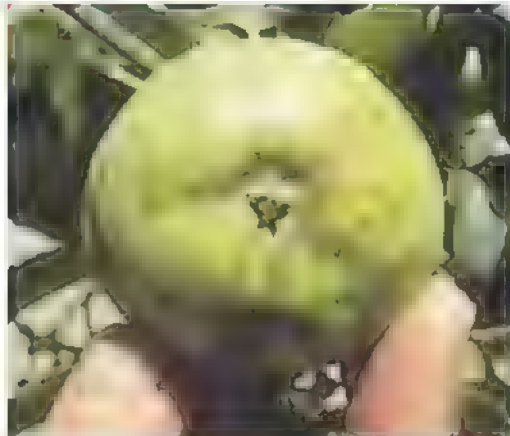


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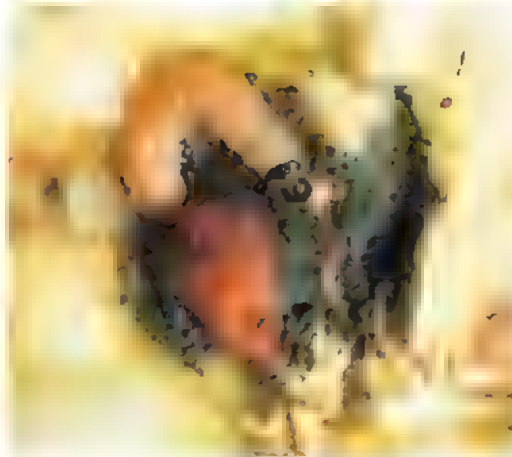
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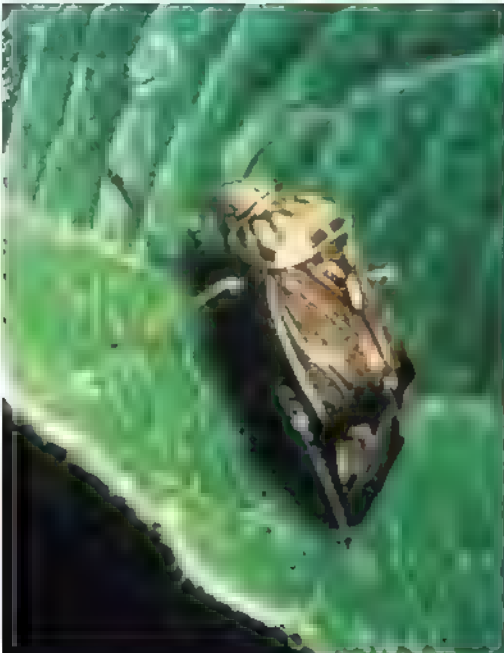
19.2.



19.3.



19.1.



19.4.



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19.5.



19.6.



19.8.



19.7.



19.9.



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Plate 19.9. Two-spotted spider mite (*Tetranychus urticae* Koch) adult female. This extremely polyphagous species has a cosmopolitan distribution.

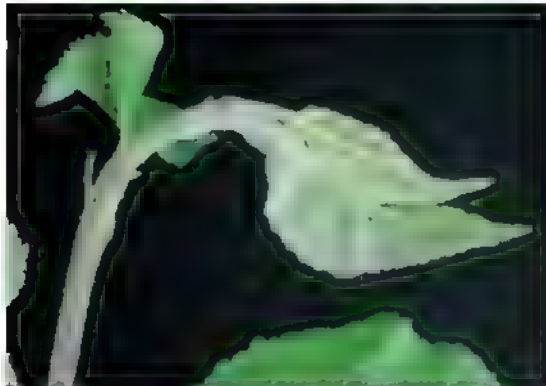
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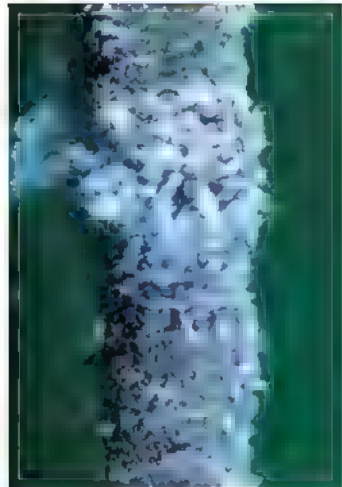
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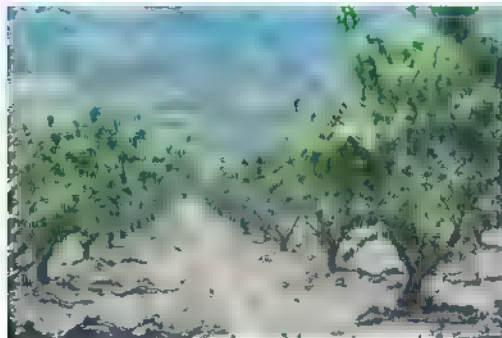
19.12.



19.13.



20.1.



20.2.



Plate 19.10. *Typhlodromus* (*Galandromus*) *occidentalis*, the principal mite predator in the arid growing regions of the western USA.

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20.3.



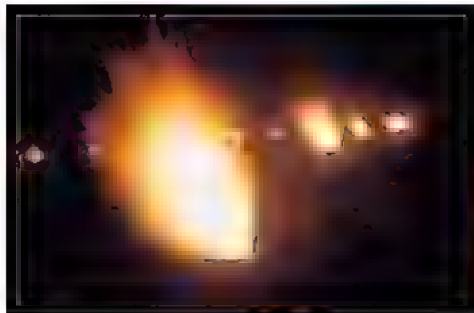
20.5.



20.6.



20.4.



20.7.



Plate 20.3. Towers used to monitor inversions and wind-machine effects.

Plate 20.4. Heater plumes.

Plate 20.5. Under-tree sprinkling for freeze protection.

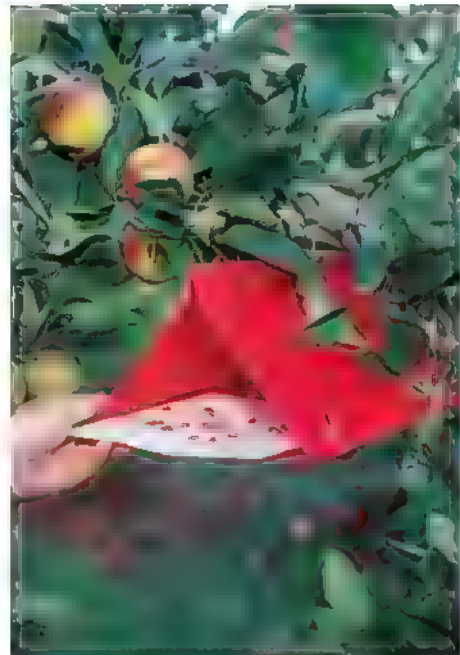
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Plate 20.7. Over-tree sprinkling for apple-bloom delay. Delayed trees (still nearly dormant) in the background are white from calcium carbonate deposition. Controls, in the foreground, are nearing first bloom.

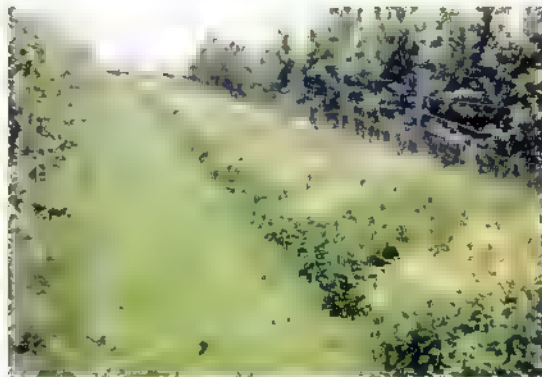
21.1.



21.2.



22.1A.



22.1B.



22.1C.

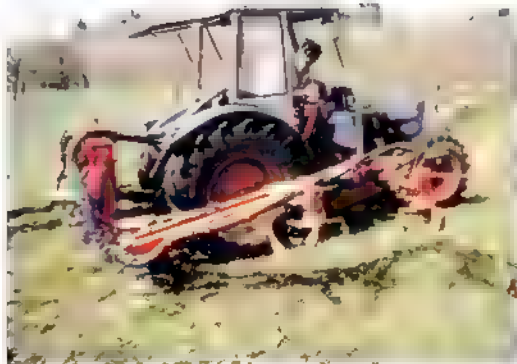


Plate 21.1. A large air-blast sprayer in operation. New methods use improved equipment with more targeted application, less persistent chemicals and timing based on economic thresholds rather than calendar-based intervals.

Plate 21.2. Pheromone traps are used for a number of purposes including detection of adult male insects, determining the efficacy of mating disruption and for arriving at spray-application thresholds.

Plate 22.1. Orchards of dwarfing trees can incorporate many practical options for increasing biological diversity and thus enhancing biological stability. (A) Strips sown in wild flowers and herbs; (B) nesting box for tits and earwig nest; (C) nesting block for wild bees.

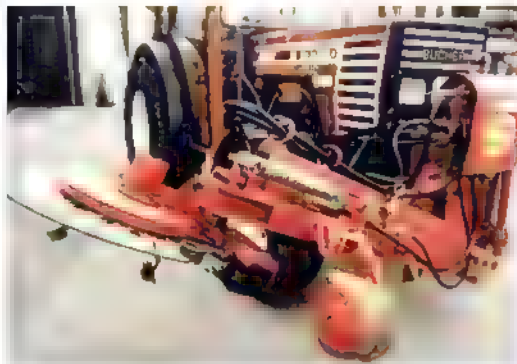
22.2A.



22.2B.



22.2C.



22.2D.



22.2E.



Plate 22.2. Soil management – methods and tools (A) The newly developed Ladurner mechanical hoe impresses with a construction guaranteeing operational comfort and good performance even in difficult conditions. (B) Undercutters (Müller RPM) Good on light soils. Problems occur in dense swards. (C) Crumbler with vertical cutters (Humus-P anet) (D) Disc plough (Spedo). (E) Thermal weed control: this device combines heat treatment with an open flame for weeding around the trunk and an infrared emitter for the strip

22.2F.



22.2G.



22.2H.



22.3.



Plate 22.2. Continued (F) FIBL's (Forschungsinstitut für Biologischer Landbau) 'sandwich system' is still in the development phase (ground-cover management, mechanical hoe for strip cultivation). It is designed to allow for the use of inexpensive and efficient mechanical hoeing equipment. The low-growing, diverse herbal ley in the middle of the in-row strip can be advantageous in supporting beneficials and in helping to maintain soil fertility.

(G) Mechanized laying of mulch sheeting. **(H)** Bark mulch applied with a mulch spreader

Plate 22.3. As synthetic thinning sprays are not permitted, the development of the rope machine, a mechanical tool for blossom thinning, has been a major step forward in solving one of the key problems of organic apple production. This development also significantly improves the conditions for converting larger orchards to organic production

23.1.



23.2.



23.3.



24.1.



Plate 23.1. Fruit inspection in a modern packing-house.

Plate 23.2. Loading a ship for export from New Zealand in the 1940s. Wooden cases are being handled individually at each stage of the transport process

Plate 23.3. Loading a ship for export from New Zealand in the 1990s. Corrugated-cardboard cartons, which have replaced wooden boxes, are stacked on fork-lift pallets for enhanced handling efficiency.

Plate 24.1. Array of processed apple products of Knouse Foods Cooperative Inc. (from Knouse Foods Cooperative Inc.).

17 Endogenous Hormones and Bioregulator Use on Apples

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Massachusetts, USA*

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17.1 Introduction

Nowhere in agriculture do plant bioregulants (PBRs) play a more important role than in apple production. While they are quite expensive, they are generally used on high-value crops where the cost can be recovered because of the higher value of the crop. Frequently, PBRs do not increase yield or, if they do, it is not the only benefit. The most likely influence of PBRs is on improving fruit quality and increasing consumer appeal.

PBRs, as discussed in this chapter, refer to three types of compounds. First, there are the hormones that occur naturally and are produced by the plant. Secondly, there is a group of synthetic plant growth regulators that are not found naturally in any plants. Thirdly, there are some compounds that are structurally very similar to hormones but they do not occur naturally in the target plants. Benzyladenine (BA) and indole-3-butyric acid (IBA) are compounds that fit into this latter category. PBRs, whether naturally occurring or synthetic, generally act by regulating or modifying natural physiological processes within the plant.

PBRs are not and should not be considered to be pesticides, since they are not toxic nor do they act directly to affect either insects or diseases. However, they can be considered important components in an integrated food-production system, since they can influence plant composition, which can have secondary but important influences in controlling insects and diseases. For example, growth retardants can affect tree microclimate by allowing better light penetration and air movement so that the fruit is less susceptible to fungal diseases, such as sooty blotch and fly-speck. Furthermore, growth retardants can make shoot tips less favourable for aphid infestation or infection from the bacterium that causes fire blight (Yoder *et al.*, 1999).

PBRs are used to control or influence many aspects of apple production, including control of preharvest drop, adjustment of crop load, regulation of flower-bud formation, modification of tree structure, suppression of growth, alteration of fruit shape, enhancement of fruit red colour and improvement in cosmetic appeal. The uses of

PBRs vary from country to country; some are registered for use in limited regions of the world. In this chapter, the main focus is on mainstream uses where their application is widespread and they represent an important component in apple production.

This chapter, is organized by physiological responses that occur in the apple. Many PBRs influence several systems in a plant. Therefore, one compound may be mentioned several times in this chapter, since it may have widespread effects on several different physiological processes.

17.2 Classification and Chemistry of PBRs

The growth of plants and the synchronous control of all physiological processes in the plant are directed and controlled by hormones (Davies, 1995). These hormones are synthesized by the plant and, for different classes or hormones, their chemical structures are quite different. Hormone concentrations, activities and responses are influenced by the environment, cultural and management activities, pests and the application of synthetic plant growth regulators. The purpose of the first part of this section is to outline briefly classes of endogenous hormones in the plant and to indicate the physiological processes where each play a key and pivotal role.

There are five generally recognized classes of endogenous plant hormones. The chemical structure of the hormone or the primary example of the class is illustrated in Fig. 17.1.

17.2.1 Auxins

The auxins were the first group of plant hormones to be discovered. Since there were no protocols that had previously been established and the very existence of compounds that regulated plant growth had not been established, it took over half a century for indole-3-acetic acid (IAA) to be discovered, its role defined and its structure identified (Thimann, 1969). Although there are a num-

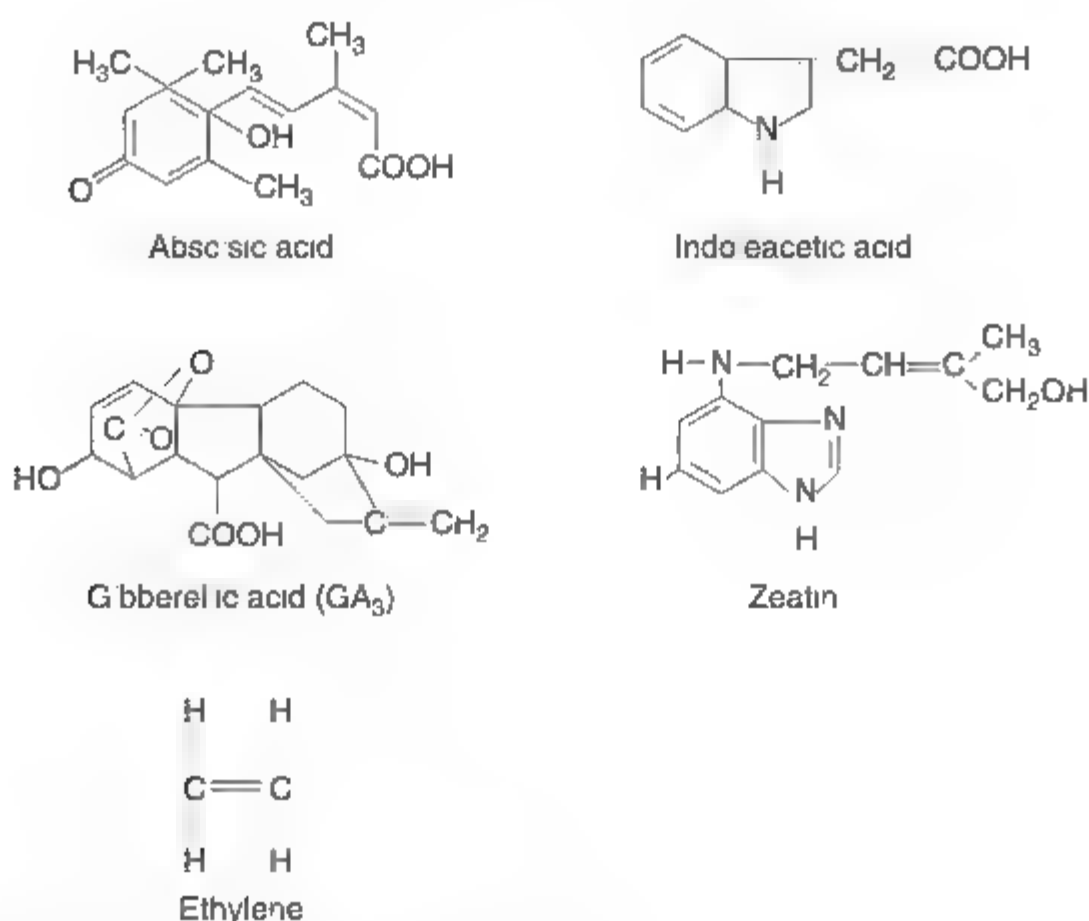


Fig. 17.1. Structures of the major endogenous plant hormones.

ber of structurally similar compounds that possess auxin activity, IAA is recognized as the dominant auxin present in most plant species. It is produced in young leaves and in the shoot apex and moves only downward in the plant in the phloem. It plays an important role in a wide range of plant processes, including apical dominance, fruit growth, fruit set, root initiation, fruit ripening, leaf senescence and fruit and leaf abscission. When auxins are exogenously applied, they usually stimulate the production of ethylene; thus some auxin effects are manifested through ethylene responses. IAA is not used commercially but the synthetic auxins naphthaleneacetic acid (NAA) and IBA are in wide commercial use.

17.2.2 Gibberellins

This is a very large family with at least 121 different gibberellins having been identified in higher plants. Unlike the auxin IAA, which is the dominant auxin in most plants, each plant species has several gibberellins, and frequently the specific gibberellin and its con-

centration are characteristic of that species (Cleland, 1969). In apple, several gibberellins have been identified, but gibberellin A₄ (GA₄) and GA₇ are generally present in the highest concentrations. Gibberellins are most noted for their ability to promote stem elongation, an effect that can be very striking at times. Several commercial plant-growth retardants, such as paclobutrazol, uniconizol, prohexadione-calcium and ancymidol, act by inhibiting gibberellin biosynthesis within the plant.

Gibberellins can inhibit flower-bud formation in many woody dicotyledonous species. The inhibitory effect of fruit on return bloom in apple is attributed to gibberellins, produced in seeds, which move out and inhibit the formation of flowers for the following season in the subtending bourse bud. Gibberellins aid seed germination by stimulating the conversion of starch to sugar.

17.2.3 Cytokinins

The compounds in this group gained their generic name because they stimulate cell division (cytokinesis) (Moore, 1989). The two

most common cytokinins are zeatin and its sugar conjugate, zeatin riboside. They stimulate cell division in fruit, especially during the early stages of fruit development following petal fall. Cytokinins are also used to stimulate cell division and shoot generation in tissue-culture propagation. Cytokinins interact with auxins in the control of apical dominance. They can overcome the inhibitory effect of auxins on lateral bud development when applied exogenously or when produced endogenously in the roots and translocated to the stems. Cytokinins can delay or defer leaf senescence. They are produced in all actively growing and dividing tissue, including leaves, shoot and root tips and seeds. However, many believe that the roots are the most important site of synthesis and, once produced, they are transported upwards in the plant xylem. BA is a synthetic cytokinin, and it is an active ingredient in the commercial products Promalin® and Accel®

17.2.4 Ethylene

Ethylene is the only plant hormone that, in its natural state, is a gas. For many years, plant physiologists refused to acknowledge the hormonal status of ethylene, because it was a gas (Abeles, 1973). Ethylene moves easily within the plant through intercellular spaces and in a dissolved form in the cytoplasm (since it is quite soluble in water). Frequently ethylene is stored within the plant as its precursor 1-amino-cyclopropane-1-carboxylic acid (ACC). Conversion from ACC to ethylene occurs following an environmental stress or triggering by an internal physiological signal. Ethylene plays a key role in fruit ripening and abscission. Apple is a climacteric fruit and it generates a large amount of ethylene as it enters the ethylene climacteric phase at maturity. The ethylene given off in this process stimulates ripening and, when translocated to the abscission zone in the pedicel, it initiates biochemical changes that result in the destruction of cells in the abscission zone. Ethylene promotes flower and fruit senescence and induction of flowering and, at

high rates, it can be a potent growth retardant. Commercially, ethylene is administered to the plant as a spray solution of the plant-growth retardant 2-chloroethylphosphonic acid (ethephon).

17.2.5 Absciscic acid

Absciscic acid (ABA) was discovered independently in two laboratories in the 1960s (Moore, 1989). One laboratory identified it as a dormancy-inducing compound, while the other laboratory found it while studying abscission in cotton. While it is associated with dormancy, acts as a growth retardant and can cause abscission in selected crops, its most important physiological function appears to be in regulating water relations within the plant (Beyer *et al.*, 1984). ABA is very closely associated with stomatal movement. When plants are stressed, ABA levels increase and cations (especially potassium) are pumped out of the guard cells, causing stomata to close. Since plants have such an active and effective metabolic system for regulating ABA levels in the plant, exogenous applications of ABA are so transient that ABA is not used commercially to regulate plant water relations.

The second and largest group of PBRs that are in general use in agriculture are synthetic organic compounds. The chemical structures and the trade name, chemical name and manufacturers of some important PBRs used on apples are illustrated in Fig. 17.2 and Table 17.1, respectively. They fall into several categories. Some very closely resemble structurally endogenous hormones. They are generally more effective than the endogenous compound they resemble, in large part because the regulatory system within a plant is not nearly as efficient in breaking down, metabolizing or inactivating these compounds with their slightly altered structure. A second category of compounds includes those that inhibit the biosynthesis or transport of endogenous hormones. These are also structurally unrelated compounds that directly or indirectly affect change within the plant and alter physiological responses.

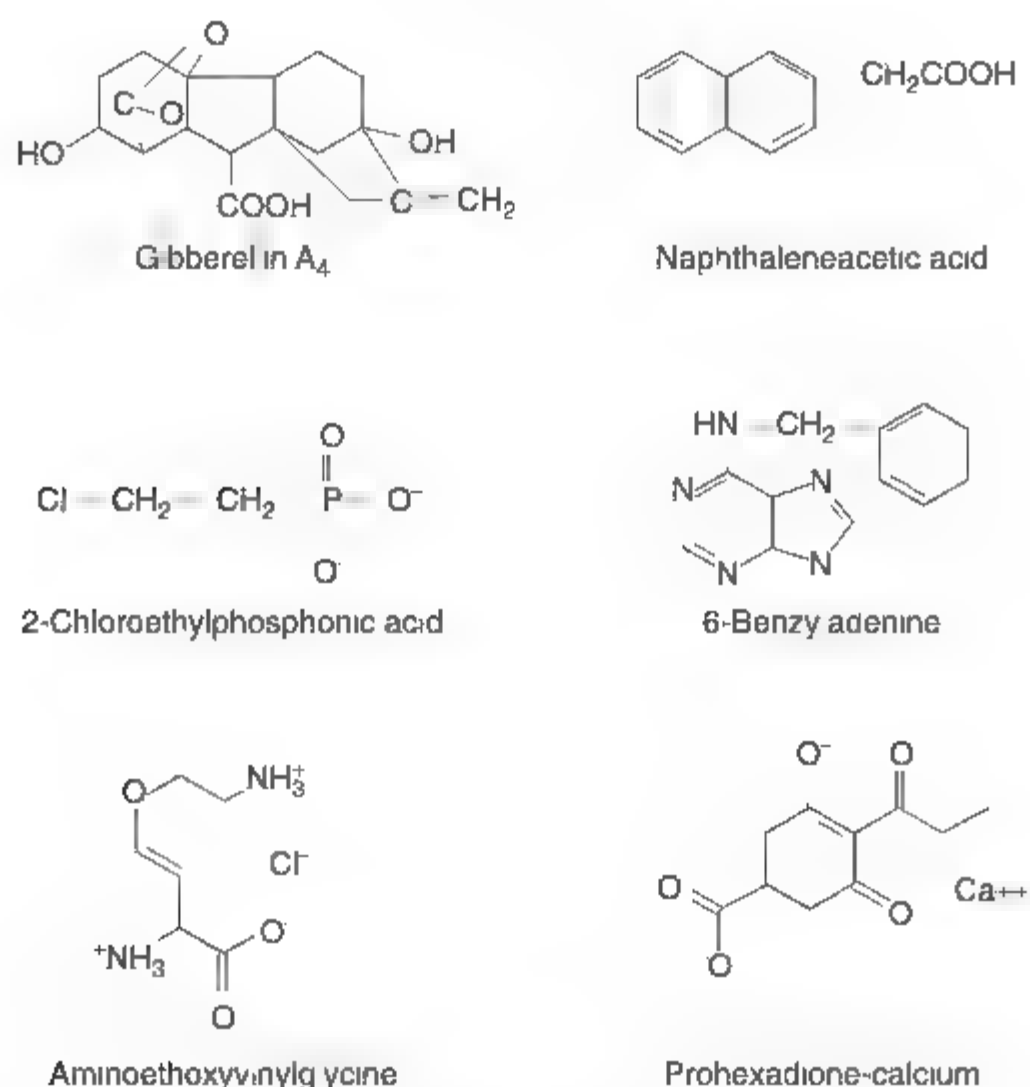


Fig. 17.2. Structures of the most commonly used plant bioregulators (PBRs) on apples.

17.2.6 Aminoethoxyvinylglycine (AVG) (ReTain®)

AVG is a naturally occurring amino acid that was first discovered by scientists at Hoffman LaRoche in the early 1970s. Its primary mode of action is to inhibit ethylene biosynthesis (Boller *et al.*, 1979). It blocks the enzyme ACC synthase, a key enzyme in the ethylene biosynthetic pathway. AVG elicits many responses in apple trees, including increasing fruit set, increasing vegetative growth, increasing fruit length/diameter (L/D) ratio, retarding fruit ripening, retarding preharvest drop and stimulating branching. Efforts to register this compound in the early 1980s were not pursued because of economic reasons. Following the loss of daminozide as a preharvest fruit-drop control compound, Abbott Laboratories resumed development of this compound for commercial use. AVG received full label registration as the product

ReTain® in 1997 for preharvest drop control and improvement of fruit quality in apples.

17.2.7 Benzyladenine (BA)

The ability of BA to increase the length of apples was recognized by Williams and Stahly (1969) several decades ago. Scientists at Abbott Laboratory combined it with GA_{4+7} in equal amounts in the proprietary product Promalin® specifically to elongate 'Delicious' apples and to promote branching on apple trees. When BA was evaluated independently, it was found that BA had several properties that are characteristic of a good chemical thinner, including ability to promote abscission, increase flower-bud formation, increase fruit size independently of thinning effects and increase fruit firmness in some instances. An altered Promalin® formulation containing primarily BA was registered as Accel® for use on apples in 1994.

Table 17.1. Common plant bioregulants (PBRs) used in apple production

PBR	Common/trade name	Chemical name	Manufacturer/seller
AVG	Retain [®]	Aminoethoxyvinylglycine	Valent USA Corporation
BA	Cylex [™]	<i>N</i> -(phenylmethyl)- <i>H</i> -purine-6-amine	Valent USA Corporation
GA ₄₊₇	Provide [®]	Gibberellins A ₄₊₇	Valent USA Corporation,
	Regulex [®]		Valent USA Corporation,
	TypRus [™]		Nufarm Americas Inc
GA ₄₊₇ + BA	Promalin [®]	Gibberellins A ₄₊₇ + <i>N</i> -(phenylmethyl)-	Valent USA Corporation,
1.8% + 1.8%	Cytolin [®]	<i>H</i> -purine-6-amine	Valent USA Corporation,
	Pomina [®]		Valent USA Corporation,
	Typy [™]		Nufarm Americas Inc;
	Perlan [®]		Fine Agrochemicals Ltd
BA + GA ₄₊₇	Accel [®]	Gibberellins A ₄₊₇ + <i>N</i> -(phenylmethyl)-	Valent USA Corporation,
1.8% + 0.18%	RiteSize [™]	<i>H</i> -purine-6-amine	Nufarm Americas Inc;
Ethephon	Ethrel [®]	2-Chloroethylphosphonic acid	Adventis Crop Protection,
	Ethephon 2		Micro Flo Company LLC
NAA	Fruitone [®] N	Naphthaleneacetic acid	Amvac Chemical Corporation
	K-Salt [™] Fruit Fix [™] 200	Naphthaleneacetic acid potassium salt	
	K-Salt [™] Fruit Fix [™] 800	Naphthaleneacetic acid potassium salt	
	Tree-Hold A-112	Naphthaleneacetic acid ethyl ester	
NAAm, NAO	Amid-th:n [®]	Naphthaleneacetamide	Amvac Chemical Corporation
Prohexadione-calcium	Apogee [®]	Calcium 3-oxido-5-oxo-4-propionyl-cyclohex-3-ene-carboxylate	BASF Corporation
	Regalis [®]		

17.2.8 2-Chloroethylphosphonic acid (ethephon, Ethrel[®])

Ethephon was the first ethylene-based plant-growth regulator to be available in the market. It was introduced in 1971 to stimulate latex flow in rubber trees. Since that time, its use has been considerably broadened and it has become one of the most useful and diversified PBRs applied. It is now registered on over 20 horticultural and agronomic crops, including fruit crops, such as apple, cherry, pineapple and grapes.

Ethylene is a hormone that influences several physiological systems within a plant. However, the problems associated with administering ethylene in its gaseous form are immense. Ethephon simplifies this and makes it extremely easy and convenient to apply precise doses of ethylene when needed. Ethephon is applied as an aqueous spray, where it is eas-

ily absorbed and readily moves into the cytoplasm, where the pH level is slightly below neutrality (pH 7). Ethephon is unstable at this pH range and autocatalytically breaks down to liberate ethylene gas within the cell. The ethylene liberated from the breakdown of ethephon frequently stimulates the plant to produce even more endogenous ethylene.

17.2.9 Indole-3-butyric acid (IBA)

Soon after the discovery of auxins, the root-promoting activity of IBA was recognized. It has been used for many years to stimulate rooting in tissue culture and in shoot cuttings taken for vegetative propagation (Hartmann and Kester, 1983). It remains today as the only hormone, or as a major component in several commercially available rooting formulations, for root induction.

17.2.10 Naphthaleneacetic acid (NAA)

NAA was one of several auxins that were identified as retarding preharvest drop in apples prior to harvest, while also promoting abscission on young developing fruit when applied soon after bloom. It is used to promote rooting in some rooting formulations. It is the only auxin to have survived over 50 years of regulatory scrutiny and remain registered for use today both as a chemical thinner and as an inhibitor of preharvest drop on apples.

17.2.11 Prohexadione-calcium (Apogee®)

Several commercially-produced PBRs are available that interfere with gibberellin biosynthesis. However, Apogee® represents a new class of gibberellin inhibitor, which inhibits GA biosynthesis at a later stage in the biosynthetic pathway and thus offers the potential of acting with fewer side-effects (Rademacher, 1991). Apogee® retards vegetative growth on apples, which improves spray penetration and coverage, reduces pruning time and provides a more open canopy that facilitates light penetration into the tree

17.3 Application of PBRs

The majority of PBRs are applied as a foliar spray and this has historically been done with a dilute application, where the spray material is applied to near the drip (or runoff) point. This was an effective approach to ensure that an appropriate distribution of the active ingredients are uniformly distributed within and to the tops of large trees propagated on seedling or vigorous clonal rootstocks. The trend for the past two decades has been to grow apple trees as smaller-stature trees at much higher densities. The use of larger equipment designed to deliver spray to the tops of large trees is inappropriate in high-density plantings because of the large amount of space required between rows. Accompanying increased tree density has been a reduction in the size of equipment used and a reduction in the volume of spray used to deliver both pesticides and PBRs.

Byers *et al.* (1971) first introduced the concept of tree-row volume (TRV) to determine the volume of spray necessary to achieve adequate coverage of trees planted at higher densities. An example of a dilute TRV calculation for an apple orchard is illustrated in Table 17.2. The concept has evolved and been

Table 17.2. Calculations of dilute volume necessary to wet apple foliage in an orchard to saturation.

Parameters to measure

Canopy height (m) – distance from first scaffold to the top of the canopy

Tree width (m) – average maximum width of a tree from branch tip to branch tip

Row length = $\frac{\text{Area of a hectare (m)}}{\text{Row width (m)}}$

Tree-row volume (TRV) or canopy (m³) –

Canopy height × Tree width × Row length

Dilute volume requirement per hectare equals about 1 l of spray for each 10 m³ of foliage

Example calculation of dilute spray requirement

Trees in a sample orchard have a canopy height of 3.75 m, a tree width of 4 m and a row width of 6 m.

$$\text{TRV} = 3.75 \times 4 \times \frac{10,000 \text{ (m}^2 \text{ ha}^{-1}\text{)}}{6} = 25,000$$

$$\text{Dilute volume} = \frac{\text{TRV}}{10} = 2500 \text{ l ha}^{-1}$$

refined in recent years. Effective and consistent use of PBRs must take TRV into account if spray applications of PBRs are applied at reduced spray volumes (Bukovac, 1980). For example, label recommendations for the use of AVG as a preharvest-drop-control compound are given in grams of active ingredient per hectare. However, this bioregulant may be applied on blocks that have a TRV ranging from 935 to 3800 l ha⁻¹ (100–400 gal acre⁻¹). Since the drop response to ReTain® is linear with the dose sprayed on the tree, one can expect a much stronger drop-control response on trees with the lower TRV. In this case, four times as much material is being applied on the leaves and fruit of smaller trees than on the larger ones. When applying PBRs at less than dilute TRV, it is always prudent to first calculate TRV and then put in the spray tank the amount of material suggested on the label for the area being sprayed. The surfactants and other spray additives to aid penetration are generally not concentrated.

There are several problems associated with the application of PBRs in low-volume sprays and these may result in variable responses (Bukovac, 1984, 1985). First, the chance of over- or under-application is accentuated since the response to most PBRs is linear with concentration or dose. When PBRs are applied as a dilute spray, the chance of over-application is minimized because excess spray will drip off the tree. Even if an error of 10% in the amount of PBR applied is made, consequences are generally not great. However, if a spray is applied in one-sixth to one-tenth the volume of water used for a dilute spray (six- to ten-fold) and the same 10% error is made, this error can be magnified 600–1000%, with resulting consequences of over- or under-application. Secondly, where a lower volume of water is used, the drying time of the spray will generally be shorter. It is generally accepted that there is reduced uptake of foliar-applied substances under such circumstances. Therefore, efficacy, even when the same amount of PBR is applied, may be diminished due to reduced uptake. Thirdly, smaller droplet sizes are generally associated with methods that apply lower spray volumes. Smaller droplets generally do not carry as far and are more affected by wind. Therefore,

spray deposition in the tops and interior of trees is often less than satisfactory

17.4 Development and Maintenance of Tree Structure

The fruiting structure of an efficient apple tree is developed during the formative years. This fruiting structure should have several characteristics: it should be developed rapidly, make efficient and effective use of the allotted space, efficiently intercept the available sunlight and possess a structure that encourages the development of an appropriate balance between fruiting and vegetative growth (Forshey *et al.*, 1992).

17.4.1 Increased lateral branching

Many cultivars, especially those that are tip bearers or those that possess a spur-type growth habit, do not naturally form an ideal structure or have an appropriate growth distribution (Elfving, 1984; Miller and Eldridge, 1986). Many cultural and management techniques are currently in use or have been evaluated to improve tree structure. These include pruning, bending, spreading, notching, deblossoming and bud removal. In general, branching in young trees is inhibited because the apical buds on a tree or shoot suppress bud break and shoot growth of buds in lower, more basal positions. Complete removal of the shoot tip by pruning usually results in the growth of two or three undesirable shoots with sharp branch angles immediately behind the cut (Forshey *et al.*, 1992). Alternatively, Promalin®, a proprietary product containing equal amounts of GA₄₊₇ and BA, may be applied to apple trees shortly after bloom to encourage lateral bud growth and to improve tree structure (Table 17.3). This product may be used on trees where the apical bud has not been removed by pruning. Consequently, the undesirable regrowth following pruning can be avoided. It is most successful when used on healthy, rapidly growing trees. It generally requires application of from 125 to 500 mg l⁻¹ with an effective surfactant, made when terminal growth is between 25 and 75 mm in

Table 17.3. Influence of BA + GA₄₊₇ and BA alone (application when shoots of 'Macspur McIntosh'/M.26 were 3 cm in length) on lateral branching and shoot growth (from D.W. Greene, 1982, unpublished results)

Treatment (mg l ⁻¹)	Spurs per cm LCSA	Lateral shoots per cm LCSA	Mean lateral shoot length (cm)	Blossom clusters per cm LCSA year after application
Control (0)	4.1a	0.7b	24.0a	11.9a
GA ₄₊₇ + BA 500	2.1b	2.6a	20.6b	0.1b
BA 500	2.7b	2.3a	17.0c	13.8a

Values with uncommon letters are significantly different at odds of 19 to 1.
LCSA, limb cross-sectional area.

length (Forshey, 1982). Rates that effectively stimulate lateral branching are usually high enough to completely defruit trees and the presence of gibberellins in this product inhibits flowering for the following year (Table 17.3). Therefore, the use of Promalin® is limited to situations where fruiting is neither anticipated nor desired for the year of application and the year after application.

Branch development can be a somewhat random event. Generally, buds that grow into good lateral shoots come from large buds and they are located either laterally or on the top of a branch. The chance of stimulating branching on a limb portion can be improved immensely by notching buds prior to Promalin® application. Notching is done using a hacksaw blade to remove a strip of bark one-third around the stem immediately above the bud that one wishes to develop into a lateral shoot (Greene and Miller, 1988; Greene and Autio, 1994). This can be done a few days either before or after full bloom.

17.4.2 Suppression of water-sprout growth

As apple trees mature, it is frequently necessary to make pruning cuts to restrict tree height or to contain trees within their allotted space. These cuts often stimulate the development and rapid growth of upright shoots that originate from latent buds within the wood (Forshey *et al.*, 1992). They are referred to as either water sprouts or suckers. They are very undesirable because they are unproductive, create unwanted shade within the canopy, impede distribution and coverage of spray materials and can foster the growth and devel-

opment of insects and diseases. They can be removed by hand, but at considerable expense. They can be pruned out but regrowth is virtually ensured when using this approach.

Control of the growth and development of water sprouts is most easily accomplished with NAA. The Tree-Hold Sprout Inhibitor® (Amvac, Los Angeles, California) is specially formulated, using the ethyl ester of NAA for sucker control, and it is more effective than other formulations of NAA, such as the sodium salt, which is used for chemical thinning (Raese, 1975). Generally, this product is mixed with 25–50% interior white latex paint, to give a final NAA concentration of 0.5–1.0% (Miller and Ware, 1980). The latex paint marks and identifies the area treated and thickens the mixture so that it remains on the treated area. It may be applied with a brush, paint roller or hand-pump sprayer with a sponge attached to the nozzle.

The NAA should be applied after pruning, during the dormant period. Both the cut surfaces and 50–75 mm surrounding the cut should be treated. However, whole branches should not be treated. As a useful guide, no more than 10% of the total limb surface area should be treated. Application should be made no later than bud break, because of the possibility of thinning, due to NAA volatility, and reduced fruit size, due to a direct effect of NAA.

17.4.3 Suppression of root suckers

Many of the most popular dwarfing rootstocks and interstem trees develop suckers at the base of trees. These unsightly shoots

serve as an entry way for fire blight into trees, harbour insects and diseases, make some orchard activities such as mowing difficult and, if unattended to, will grow up into a tree. Control of these is accomplished either with the use of NAA ethyl ester as the Tree-Hold Sprout Inhibitor® formulation (Miller, 1977) or in Europe and the southern hemisphere with Tipoff® (Midox Ltd, Kent, UK), which contains the free acid of NAA in an emulsion with decanol. Root suckers are first cut to the ground, generally during the dormant season and when the new root suckers are 10–30 cm in height, they are treated (Miller, 1989). It is recommended that the period from bloom to 4 weeks after bloom should be avoided, because the volatility of NAA may cause fruit thinning. Tree-Hold® is prepared as described for control of water sprouts, except that water is used instead of the latex paint, while when Tipoff® is used it is diluted with two parts water. Both compounds are sprayed on the foliage of the root suckers. This should only be done under calm wind conditions and using a sprayer that does not generate many small droplets that will drift. Since thorough coverage is critical and weeds may protect root suckers from the spray, application of a contact herbicide, such as gramoxone, a few days before application may improve control.

17.5 Vegetative-growth Control

There is a very delicate balance between vegetative growth and cropping in apple trees. This balance may be disrupted by abnormal or catastrophic weather or by management mistakes that reduce fruit set or crop load and result in excessive vegetative growth. Vigorous growth can negatively influence fruit quality, productivity, pest control and profit. Failure to control vegetative growth adequately in high-density blocks may ultimately result in the necessity to remove the block because of poor fruit quality and low productivity. There are a number of no-chemical ways to restrict vegetative growth, including dormant, summer and root pruning, ringing and scoring, limb spreading,

restricted fertilization and the control of water (Ferree, 1981). Used alone, many of these techniques may be only marginally effective. The two PBRs that hold the greatest commercial potential to control vegetative growth on apples are Apogee® and ethephon.

17.5.1 Growth control with Apogee®

Apogee® is the newest growth retardant to receive full label registration. Like several other growth-retarding chemicals, it acts by inhibiting gibberellin biosynthesis (Evans *et al.*, 1999). However, it is different in that it blocks the gibberellin biosynthetic pathway at a point different from other known GA inhibitors. Once applied, it requires between 10 and 14 days to slow growth. It degrades within the tree in a few weeks, so repeat applications are usually necessary to maintain growth control throughout the whole growing season (Byers and Yoder, 1999). Patterns of terminal growth and fruit-set characteristics differ among fruit-growing regions, and the response to Apogee® appears to differ depending upon the area of the country where it is used (Unrath, 1999). Therefore, regional interpretation of the label is necessary to get the maximum response desired.

The initial application of Apogee® is made as soon as there is sufficient leaf area to absorb the chemical – generally at late bloom or petal fall, when shoots are 25–75 mm in length. The growth response of ‘Macoun’ apple trees to one petal-fall application of prohexadione-calcium at a high rate or three applications at a lower rate is illustrated in Fig. 17.3. It has no detrimental effects on bees so the first application can be made even before bees are removed from the orchard. The initial application should be at a TRV-adjusted concentration of 82 125 l⁻¹. Application can be concentrated as long as coverage is uniform. Apogee® should be applied with a surfactant at a rate of 0.5–1.0 ml l⁻¹ to assure wetting and good coverage. Apogee® will precipitate out in the spray tank if the water it is applied in is ‘hard’ (i.e. has a high pH and contains high levels of calcium carbonate). Under these

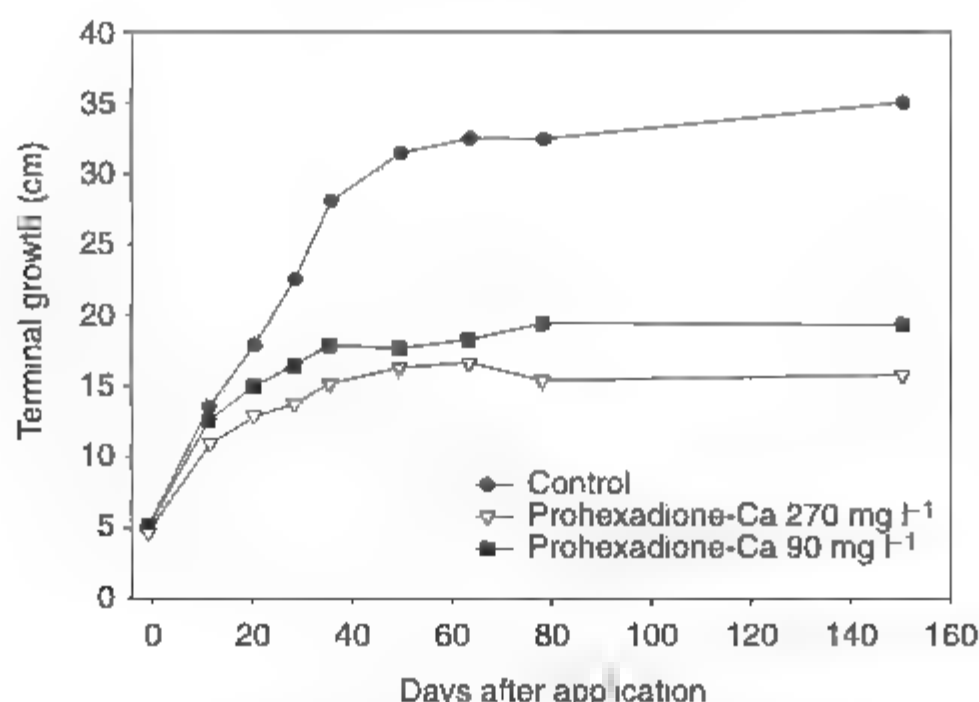


Fig. 17.3. Growth control of 'Macoun'/M 7 apple trees using one petal-fall application of prohexadione-Ca at 270 mg l⁻¹ or three applications of 90 mg l⁻¹ at approximately 2-week intervals starting at petal fall (after Greene, 1999)

circumstances, the label recommendation is to add an equal weight of ammonium sulphate in the spray tank with Apogee®. The prohexadione-calcium formulation being prepared for sale in Europe, and perhaps other countries, contains ammonium sulphate; thus additional ammonium sulphate will not be necessary.

Prohexadione-calcium may increase fruit set. This response is particularly pronounced in areas that experience cool weather during the post-bloom period. Its effect is linear with increasing concentration (Greene, 1999). In the majority of cases where 250 mg l⁻¹ is used, fruit set will be increased, with a corresponding decrease in fruit size. In these cases, more aggressive chemical thinning is necessary to reduce crop load down to desired levels.

Growers are given a number of treatment choices involving concentration and numbers of applications to make under several growth-control circumstances. Experts who have worked with this compound for several years do not agree on the amount to apply initially, how many applications to make and how to decide when it is appropriate to make additional applications. Growers may be required to use the trial-and-error method initially to determine the best combinations for use in their situation.

However, a consensus is emerging where the scenario that will probably be adopted by most growers is to make an initial application at 25–50 mm of growth using 82–125 mg l⁻¹. If a block is vigorous and the grower does not want to assume the responsibility of monitoring the resumption of growth on a nearly daily basis, a second application of 62–82 mg l⁻¹ should be made 2 weeks after the first. That may be all of the prohexadione-calcium required in cooler northern regions where terminal growth stops early (Greene, 1999). Additional applications of 62.5–125 mg l⁻¹ may be required in warmer growing areas with a longer growing season (Unrath, 1999).

17.5.1.1 Use of prohexadione-calcium to control fire blight

Prohexadione-calcium will control fire blight on shoots by inducing resistance in the tree (Yoder *et al.*, 1999). For it to be effective, it must be applied and growth retardation must occur before infection (Table 17.4). Generally, this requires that application must occur a minimum of 10–12 days before infection. The active ingredient in prohexadione-calcium appears not to have any direct effect on the fire blight bacteria. It is not effective on blossom blight, so tradi-

Table 17.4. Suppression of fire blight incidence and canker length by applications of prohexadione-Ca and streptomycin to 'Golden Delicious' apple trees, Winchester, Virginia, 1997 (from Yoder *et al.*, 1999).

Rate (mg l ⁻¹) and timing		% Inoculated shoots infected 17 July; inoculated on		Mean canker length (cm) 17 July of shoots inoculated 4 June
Prohexadione-Ca 21 May	Streptomycin 27 May	28 May	4 June	
0	0	48a	75d	12.1b
125	0	32ab	20b	2.2a
250	0	25ab	13b	0.4a
0	100	18a	50c	4.8a
250	100	16a	2a	0.7a

Values with uncommon letters are significantly different at odds of 19 to 1

tional measures using streptomycin are appropriate. Application of prohexadione-calcium to control fire blight should be made at the same time as applications to control growth, when shoots are 25–50 mm in length, at a rate of 125 mg l⁻¹. A second application may be required 3 weeks later to get the best results.

17.5.2 Growth control with ethephon

Ethephon is an extremely effective growth retardant. It is also an effective fruit thinner, and it can thin over the longest span of developmental stages of any of the commercially used chemical thinners (see also Chapter 16). Because it acts both as a growth retardant and as a thinning agent, care must be exercised to minimize thinning effects when used on bearing trees.

Occasionally, the fruit crop on blocks of bearing trees is lost due to frost. There is a delicate balance between vegetative growth and fruiting, and the high vigour caused by crop loss may tip the balance so far in favour of vegetative growth as to make it difficult to bring the planting back into an appropriate balance between vegetative growth and fruiting in successive years. Ethephon applied at 500 mg l⁻¹ when terminal shoots are 10–15 cm in length may be useful in retarding growth and preserving an appropriate balance between vegetative growth and fruiting in the year that frost damage occurs. A second application of ethephon later, at a lower rate, may be appropriate in warmer areas with a longer growing season (Greene, 1996b). Growth retardation and increased return bloom following ethephon application and compared with scoring on 'Delicious' apple trees are illustrated in Table 17.5

Table 17.5. Influence of ethephon application or scoring 12 days after bloom on terminal growth and flower-bud formation the year after application on 6-year-old 'Richared Delicious'/M 7 (from Greene and Lord, 1978)

Treatment (mg l ⁻¹)	Terminal growth (cm)	Blossom clusters per cm LCSA year after application
Control	55a	3.0c
Ethephon 500	38b	7.2b
Ethephon 1000	35b	9.9a
Scoring	38b	8.8ab

Values with uncommon letters are significantly different at odds of 19 to 1. LCSA, limb cross-sectional area.

17.5.2.1 Postbloom application on non-bearing trees

On non-bearing trees ethephon should be applied at 250–500 mg l⁻¹, when shoot growth is 7–12 cm in length. Growth control is more difficult on non-spur cultivars and on trees budded on vigorous rootstocks. Increased flower-bud formation can be expected the following year.

Ethephon may be used on bearing trees but precautions must be taken to minimize thinning if a reduction in crop load is not desired. One strategy to avoid thinning is to wait until the end of June drop (northern hemisphere) before applying ethephon. Using this approach, growth control will be less than if applied earlier, little or no thinning will take place and some increase in return bloom will occur. These treatments may, however, advance ripening, which may result in early preharvest drop and early breakdown of starch within the fruit.

17.6 Influence on Flowering and Fruit Set

17.6.1 Promotion of flowering in non-bearing trees

Ethephon is registered to promote flower-bud formation on young bearing trees when applied at 300–600 mg l⁻¹ shortly after bloom. However, the apple trees now being planted are being established at higher densities and are being propagated on dwarfing rootstocks. They generally bloom and set fruit early, reducing the need to promote further flowering. Since early production is a key to success in these blocks, the use of flower-bud-promoting sprays is usually not necessary. The use of ethephon to promote flowering on non-bearing trees is generally restricted to vigorous rootstock/scion combinations, where flowering can be delayed for several years.

17.6.2 Promotion of flowering on bearing trees

Flowering on bearing trees is most often regulated by promoting fruit abscission through the use of chemical thinners (Chapter 16).

Often this is all the intervention necessary to ensure good repeat bloom. However, there are situations where further promotion of flowering is appropriate. Growers have two PBRs available to promote flowering on bearing trees.

NAA may be applied after the time fruit are susceptible to thinning but before the flower-bud initiation period has ended, using 3–5 mg NAA l⁻¹. The exact time will vary from year to year but this period would roughly range from the time fruit are 20 mm in diameter to 8 weeks after bloom. The use of NAA at these low rates is unlikely to affect fruit size.

Multiple doses of ethephon at 100–200 mg l⁻¹ may also be applied, starting at the end of June drop. Byers (1993) enhanced flowering on 'Starkrimson Delicious' by applying either 12 weekly or six biweekly sprays of either 100 or 200 mg ethephon l⁻¹, respectively. Some growth control was achieved with these treatments and fruit ripening was advanced, as determined by starch rating.

17.6.3 Inhibition of flowering

Regulation of flowering and the maintenance of an appropriate balance between vegetative growth and flowering is usually accomplished on bearing trees by chemical thinning during the first 3 weeks after bloom on heavily blooming trees. Young developing fruit are removed during this time, leaving some spurs with no fruit, which will allow flower-bud formation for the following year. It is possible similarly to establish an appropriate balance between vegetative growth and fruiting by inhibiting flower-bud formation during times when there is reduced flowering on bearing trees. Gibberellins are produced by the seeds. These migrate out and move to the bourse bud, where they inhibit flowering for the following year. Commercially available formulations of GA₃ (ProGib®) and GA₄₊₇ (Provide®) may be applied during the first 4 weeks after bloom, at rates of 50–200 mg l⁻¹, and this inhibits flower-bud formation for the following year (Greene, 1989). This has not become a viable way to regulate flower-

ing in bearing trees because of several negative side-effects. GAs reduce seed number and seeds are important to aid the uptake and mobility of calcium to the fruit within the tree (Bamlage *et al*, 1990). Inhibition of flowering by the use of GAs has not been sufficiently perfected for precise and predictable reductions in flowering to be achieved (Greene, 2000). Poor pollinating weather may occur at bloom, which would make it advantageous to have more, rather than less, bloom to get a commercial crop.

Inhibition of flowering may be a viable technique on young trees that are just starting to come into production. The majority of apple trees being propagated in the USA and elsewhere are propagated on very precocious rootstocks. Early flowering and fruit set can slow tree growth to the extent that trees are prevented from filling their allotted space and never reach their full yield potential. Furthermore, heavy set on young trees may cause leader or limb breakage, which can result in substantial structural damage to the tree. Sprays of 250–500 mg GA₄₊₇ or GA₃ l⁻¹ can substantially reduce return bloom on young apple trees, thus improving tree growth (Table 17.6; Unrath and Whitworth, 1991).

17.6.4 Increasing fruit set

Even though trees may flower, there are occasions when these flowers fail to set and develop into a commercial crop. This may occur because of a weather event such as a frost or poor pollinating weather, or it may

be due to nutritional or physiological status that result in stress. PBRs in these circumstances may be used to enhance fruit set. Mixtures of chemicals containing auxins, gibberellins and cytokinins have been used in Europe to increase fruit set on pear trees that have been frost-damaged, but the response is less predictable on apples (Goldwin, 1986). Gibberellins may increase fruit set on apples but their application is unlikely to become a widespread commercial practice for several reasons (Dennis, 1973). The fruit-set response is erratic and unpredictable, and the fruit that are set as a result of GA application are generally small and have a reduced storage potential. Furthermore, GAs inhibit flower-bud formation for the following year.

Prohexadione-calcium, when applied to control terminal growth and retard fire blight, may increase fruit set (Greene, 1999). The response is most prominent when rates above 125 mg l⁻¹ are used, when it is used in cooler climates or when cooler weather conditions occur during the post-bloom period. Increased fruit set following Apogee® application usually results in reduced return bloom the following year.

It is well known that AVG can increase fruit set on apple (Williams, 1980). Generally rates between 125 and 500 mg l⁻¹ are required. Application can be made shortly before harvest or soon after bloom but before the start of June drop. It can increase fruit set on young apple trees that are just starting to come into production but, as with other ways of increasing set, it frequently reduces return

Table 17.6. Influence of GA₄₊₇ application made 4, 5, 9, 13 and 18 weeks after petal fall on return bloom of 'Redchief Delicious'/M 7 apple trees (from Unrath and Whitworth, 1999).

Gibberellin concentration (mg l ⁻¹)	Blossom clusters per cm LCSA the year after application	Bloom suppression (%)
0	7.8a	0
250	0.4b	95
500	0.1c	99

Values with uncommon letters are significantly different at odds of 19 to 1

LCSA, limb cross-sectional area.

bloom for the following year. Increased fruit set with the currently available commercial formulation of AVG is not on the ReTain® label at this time and, unless the cost of this product is reduced, increased fruit set is not likely to be a use of this product.

The growth retardant paclobutrazol (Cultar®) when applied as a foliar spray can increase fruit set the year following application (Miller and Sweitlik, 1986). Increased fruit set can occur for several more years if higher rates are used or application is made as a soil drench. Extreme care must be taken when using this compound, since residues may remain in the ground and retard growth subsequently for several years.

17.7 Control of Preharvest Drop

One of the greatest problems that apple growers face is the drop of fruit before it can be harvested. Some cultivars, such as 'McIntosh', are particularly prone to this problem. Drop on many cultivars can exceed 20%, but on the drop-prone cultivars it is not uncommon to have losses exceed 50% (Greene, 1996a). In areas where one or two cultivars are dominant, growers are frequently faced with the challenge of harvesting a large portion of their crop in a short period of time before fruit condition declines and fruit are lost due to drop. Warm weather before harvest, drought stress and foliage damage from insects and diseases all increase drop (Byers, 1997). Several compounds have been used over the past half-century to control preharvest drop, but, due to regulatory reasons, only AVG (ReTain®) and NAA are currently available for widespread commercial use.

17.7.1 Control of preharvest drop with AVG

As apples ripen, they produce ethylene in large amounts, which moves through the intercellular spaces in the fruit and through the pedicel to the abscission zone, where it stimulates the synthesis of enzymes, which ultimately break down the cells in the abscission zone. It is believed that the mode of

action of AVG is to inhibit ethylene biosynthesis in the fruit. In the fruit treated with AVG, ethylene production will be reduced, synthesis of enzymes responsible for the destruction of cells in the abscission zone will be delayed and the fruit will remain on the tree for a longer period of time.

Label recommendations for the use of AVG suggest that it should be applied at a rate of 125 g (a.i.) ha⁻¹, regardless of tree size or TRV. However, the effectiveness of AVG as a drop-control compound is linear with the amount applied. Therefore, better drop control can be expected on smaller trees in blocks with a low TRV, simply because more compound is delivered per area of tree than on larger trees.

The suggested time of application of AVG is 4 weeks before anticipated normal harvest. Applications made earlier than this run the risk of losing drop control before harvest and, if application is delayed, fruit effects will be diminished, some drop may occur before drop control is effective and harvest may be unnecessarily delayed, because a preharvest interval of 28 days is required between application and harvest. The silicone-based surfactants 'Silwet' and 'Sylgard' should be included at 0.05–0.1% to improve the effectiveness. Concentrate application can be done as long as the spray volume is large enough to ensure both good coverage and adequate spray distribution within the tree. The effectiveness of AVG and NAA as drop-control compounds on 'McIntosh' apples is illustrated in Fig. 17.4. Rain soon after application may reduce the response to AVG. However, if one of the recommended silicone-based surfactants is used and AVG completely dries on the foliage, rain will have little effect, if any, on reducing preharvest drop (Greene *et al.*, 2000).

17.7.2 Control of preharvest drop with NAA

It has been known for over a half a century that auxins can inhibit abscission. Many synthetic auxins inhibit preharvest drop and several of these have been used commercially. NAA, however, is the only auxin registered for control of preharvest drop.

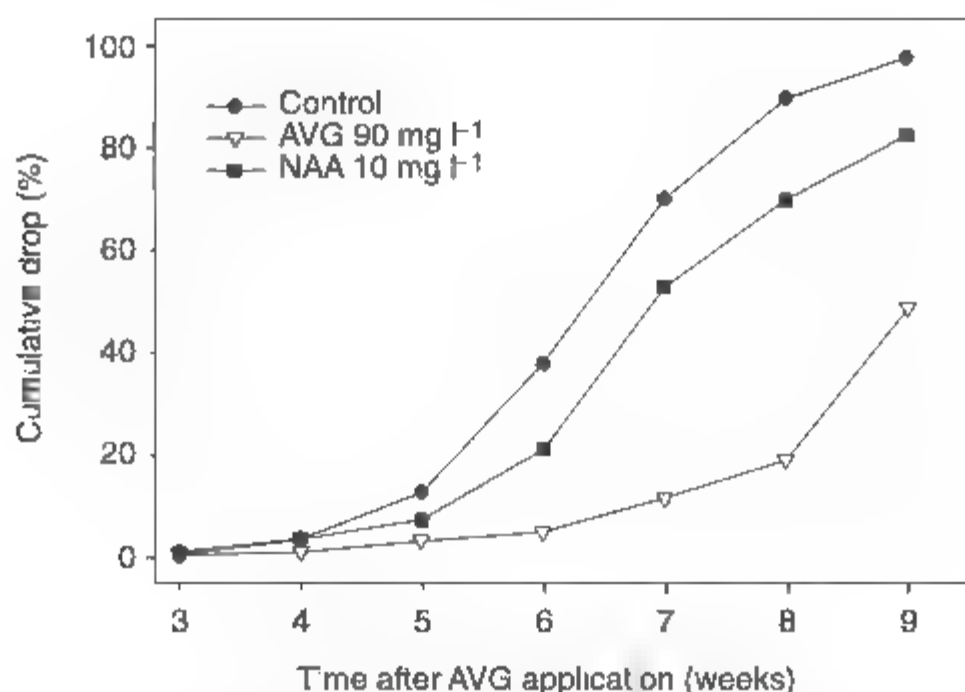


Fig. 17.4. Influence of 90 mg aminoethoxyvinylglycine (AVG, ReTain®) l⁻¹ and 10 mg naphthaleneacetic acid (NAA) l⁻¹ on preharvest drop of 'McIntosh' M 26 apples. AVG application was made with 0.01% Silwet surfactant on 15 August at the calculated dilute tree-row volume (TRV). NAA application was made as a dilute TRV application on 11 September when preharvest drop was just starting. (From D.W. Greene, Massachusetts, unpublished data.)

17.7.2.1 Label-recommended use of NAA

NAA is used at rates between 5 and 20 mg l⁻¹ and it should be applied before significant drop begins. Many of the failures or poor response of NAA to retard drop can be attributed to late application, when drop is already under way (Fig. 17.4). Normally 1-2 days are required for NAA to become effective. If drop has started, it may require up to 5 days for NAA to slow drop. NAA is effective for 7-12 days and a second application will be necessary, therefore, to reliably retard drop after 10 days. Fruit softening and reduced storage life are likely if warm weather follows application or if harvest is delayed until ripening has been substantially advanced.

17.7.2.2 Drop control using NAA preload

Marini *et al.* (1993) reported that repeated applications of NAA well in advance of the start of preharvest drop may be more effective on 'Delicious' than when NAA is applied just once prior to ripening. Unrath (1996) suggested that four weekly applications of NAA at 5 mg l⁻¹ started 4 weeks before harvest (preloading) effectively controlled drop and it did not have adverse

effects on fruit flesh firmness. The superior performance of NAA preload over conventional application is illustrated in Fig. 17.5. This approach, however, has not been effective for controlling drop on 'McIntosh' in the north east of the USA (D.W. Greene and W.R. Autio unpublished results).

17.8 Improving Fruit Appearance and Shape

Apples are just one of many choices of fruits and vegetables now available to consumers. The decision to purchase a product may be spontaneous and may be based solely on appearance and attractiveness. Therefore, any PBR application that improves fruit appearance is also likely to improve fruit sales and product movement (Looney, 1983, 1996).

17.8.1 Improving fruit shape

'Delicious' remains a dominant apple cultivar in the market today. A 'Delicious' that is blocky in shape and has prominent calyx lobes is perceived by the buying public to be preferred and have better quality. The

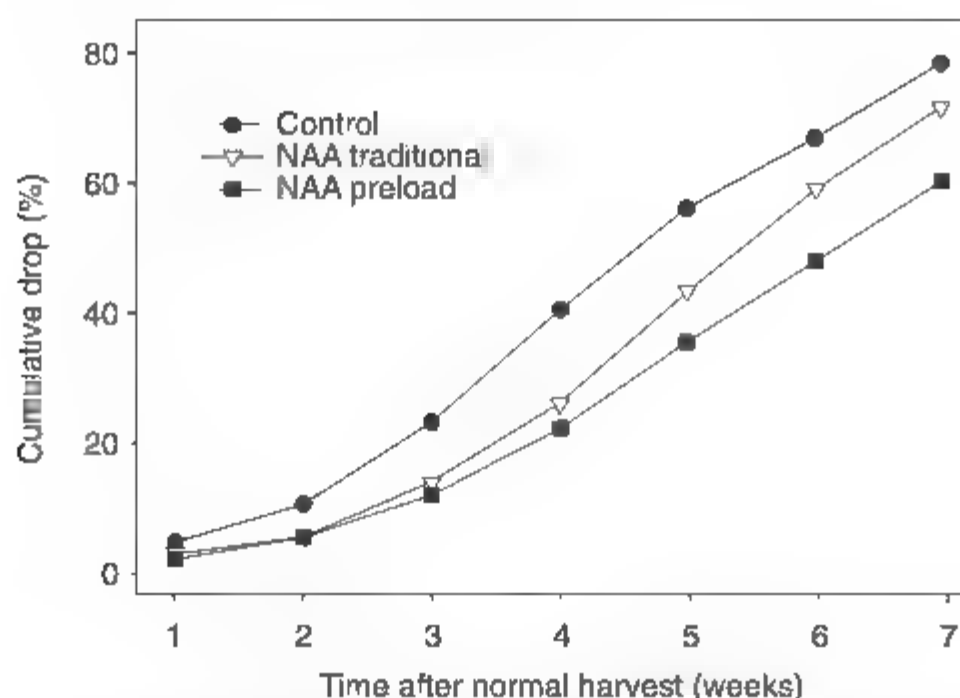


Fig. 17.5. Preharvest drop of 'Delicious' apples following NAA application – a 10-year average between 1991 and 2000. Traditional NAA application involved 10 mg l^{-1} at the start of harvest and a second 10 mg l^{-1} 7 days later. Preload NAA involved application of 5 mg l^{-1} 4, 3, 2 and 1 week before the anticipated start of harvest. (From C. Richard Unrath, North Carolina, unpublished data.)

proprietary product Promalin®, which contains equal quantities of GA_{4+7} and BA, is used to elongate fruit so that they have a 'typier' appearance. Promalin® is applied at a rate of $1.17\text{--}2.34 \text{ l ha}^{-1}$. If a surfactant is used, the effect of Promalin® is increased and fruit thinning is also increased. Promalin® should be applied at the first favourably warm weather opportunity after the king flower opens. Promalin® will thin young trees, so use of this product should be restricted to use on mature blocks or on young trees that are approaching stable production. Rates above 50 mg l^{-1} may result in reduced return bloom. It is not recommended to use NAA on 'Delicious' trees that have previously been sprayed with Promalin®, since small seedless fruit may be produced and they frequently persist to harvest.

17.8.2 Improving fruit finish

Moist, humid conditions, with rain and fluctuating temperatures, frequently result in fruit russetting on susceptible cultivars, such as 'Golden Delicious'. If severe, russet may lower fruit grade and result in a lower

price to the growers. Even if the russet is not severe, it makes fruit less attractive to consumers (Looney, 1993). Russetting in apples is reduced by Provide®, a product containing GA_4 and GA_7 in approximately equal amounts (Greene, 1993). The label recommendation is to apply two to four sprays of $475\text{--}950 \text{ ml ha}^{-1}$ at 7–10-day intervals starting at petal fall. The label restricts the amount that can be applied to $99 \text{ g (a.i.) ha}^{-1}$. Early applications are more effective than later applications, so, if only two sprays are applied, they should be made during the first 2 weeks after petal fall. The use of a surfactant with Provide® is not recommended, since the surfactant itself may cause some russetting. Application is made at less than TRV, frequently 935 l ha^{-1} . Since gibberellins inhibit flower-bud formation, even the relatively small amounts used to inhibit russetting may have a negative influence on flower-bud formation for the following year.

Provide® may also suppress cracking on 'Stayman' apples if application is made at least 2–3 weeks before cracking is likely to begin. Application rates of $1165\text{--}2330 \text{ l ha}^{-1}$ per spray are made 2–3 weeks apart. The addition of a surfactant is recommended.

17.9 Influencing Fruit Maturity and Quality

It is to the advantage of both consumers and orchardists to have attractive, high-quality, freshly picked apples available for sale over a longer duration than the normal harvest period for a cultivar. Several PBRs used alone or in combination can advance the harvest season by triggering early fruit ripening or extend the normal harvest season by delaying ripening. The quality of fruit available to consumers from these sources is increased.

17.9.1 Advancing fruit ripening with ethephon

If fruit are harvested before they are physiologically mature, they will be tart, tannic, and starchy, lack sweetness and not have the characteristics typical of the cultivar. Sale of inferior-quality fruit early in the season may depress future sales because consumers have had a bad eating experience at the beginning of the season. Ethephon is used to advance ripening of apples to provide a higher-quality product earlier in the season.

Ethephon should be applied between 1 and 3 weeks before normal harvest at concentrations ranging from 62.5 to 125 ml per 100 l water (based upon a dilute TRV application). Increased red colour will be noted within 5–7 days. Flesh softening will accompany red colour development. The closer the application is made to the time of normal harvest, the shorter the time required to observe a colour and a maturity response.

A preharvest drop strategy will be necessary if ethephon is used. Normally 10–20 mg NAA l⁻¹ is used for this purpose and it is effective for 7–12 days. The NAA can be applied when the ethephon is applied or it can be delayed for 3–4 days. Application of NAA with the ethephon ensures the presence of a drop-control compound if poor spray weather occurs when the NAA is applied. Alternatively, a delay in application is a strategy that can be used to extend preharvest-drop control for several additional days where just one application of

NAA is applied. Treated fruit should be monitored daily, once ripening is observed to start. Ripening advances much more rapidly than on untreated trees, and over-ripening will occur if fruit are not harvested at the appropriate time.

Ethephon-treated fruit should be treated differently following harvest. The storage life and the shelf-life may be reduced. In some years there may be no apparent effect, while in others the effect may be dramatic. Factors that may substantially reduce the storage life of ethephon-treated fruit include using a high concentration of ethephon, a long time interval between application and harvest, the occurrence of high temperatures during the time the fruit are on the tree and a long time interval from harvest until internal fruit temperature is reduced to 0°C in storage. Yield will be reduced because fruit will be harvested 1–2 weeks earlier than normal. Fruit increase in size about 1% day⁻¹ while they remain on the tree; thus harvesting fruit 15 days earlier than normal will result in a potential reduction in yield of 15%.

17.9.2 Increasing red colour with ethephon

Nearly all red-colouring cultivars of apples benefit from additional colour. Furthermore, the development of suitable red colour is the factor that frequently determines when a grower starts to harvest a block of fruit. Ethephon application of 31–62 ml 100 l⁻¹ water (based upon a dilute TRV application) made 7–10 days before anticipated harvest may increase red colour. Improved red colour and reduction in flesh firmness following ethephon application is illustrated in Table 17.7. This use comes with some risk, because there is the potential to reduce fruit storage life. It should be noted that ethephon will not completely overcome conditions unfavourable for development of red colour. At elevated temperatures, fruit ripen at an accelerated rate, while red colour may increase little. It is important to harvest fruit before fruit condition is lost, and to cool the fruit immediately. Good exposure of the fruit to light is an important component when using ethephon. Experience has shown that

Table 17.7. Influence of preharvest application of ethephon on 11 August on red-colour development and flesh firmness of 'McIntosh' apples at harvest on 25 August (from Greene *et al.*, 1977)

Ethephon concentration (mg l ⁻¹)	Red colour (%)	Flesh firmness (N)
0 (Control)	35c	66.0a
125	57b	63.7b
250	73a	63.3b

Values with uncommon letters are significantly different at odds of 19 to 1

ethephon works best on young, well-pruned trees. Ethephon should not be used on large, dense trees or poorly pruned trees where fruit may ripen excessively before adequate colour develops.

17.9.3 Delaying ripening and improving fruit quality with ReTain®

In apple-growing areas where one cultivar predominates or where the time of ripening of two or more cultivars overlaps, orchardists are challenged to harvest the fruit in a timely manner while maintaining fruit quality. In addition to retarding preharvest drop, application of ReTain® at 123.5 g (a.i.) ha⁻¹ 4 weeks before anticipated normal harvest will delay ripening of fruit. All of the application considerations mentioned earlier for the use of ReTain® use in drop control are also appropriate for delaying maturity. Ripening can be delayed by 5–14 days, depending upon the weather and cultivar. Red-colour development, flesh-firmness loss and the degradation of starch are all delayed. There has been some concern expressed over the reduction in red-colour development, since colour is a factor that determines fruit grade. However, most pomologists now agree that reduced red colour is a direct consequence of delayed ripening. When red-colour development is compared on fruit at a comparable stage of maturity, ReTain® does not reduce red colour: it just delays development.

There are differences among cultivars related to the time ReTain® delays ripening

A delay of ripening of 7–12 days is common in cultivars that produce large amounts of ethylene, such as 'McIntosh'. Delay in ripening of some other cultivars, such as 'Gala', which are characteristically low ethylene producers, may be as long as 4 weeks.

The primary mode of action of ReTain® is to inhibit ethylene production. Consequently, apples that have been treated with ReTain® will lack many of the aromatic components and flavours associated with the process of ripening. While this may not be a problem with some less flavourful cultivars, such as 'Delicious', this reduction in taste can be very apparent and of some concern with new cultivars that were selected in large part because of their superior taste.

Some cultivars, such as 'Delicious', develop water-core (an accumulation of sorbitol in water-soaked areas within the fruit) and, if severe, this disorder can lead to the development of senescent breakdown in storage. ReTain® will delay and reduce the amount of water-core development. The increased firmness of fruit following ReTain® application has also been demonstrated. However, the response is quite erratic and unpredictable. In some years firmness differences of 1 kg have been noted between ReTain®-treated and control fruit, while in others differences are minimal. Pomologists still do not know what causes the differences and how to predict the response. Equally variable and unpredictable is the firmness response of fruit coming out of controlled-atmosphere storage.

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18 Diseases of Apple

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18.1 Introduction

Apples are host to over 70 infectious diseases, the vast majority of which are caused by pathogenic fungi (Table 18.1). Apples are also susceptible to diseases caused by bacteria, phytoplasma and virus/virus-like agents. The authors discuss several but not all economically important pre- and postharvest apple diseases in this chapter. Readers should keep in mind that some of the diseases discussed might be major in some areas and minor in others. Others (e.g. fire blight) are of importance or potential importance wherever apples are grown. In most apple-producing regions, disease control is a major annual expense for the grower. For example, in the eastern USA, the management of apple scab can require eight to ten protective fungicide applications annually. In those areas, the apple grower must manage early-season diseases, such as apple scab and cedar apple rust, as well as a group of diseases termed 'summer diseases'. Conversely, in the arid production regions of the Pacific Northwest, these diseases are non-existent or sporadic in nature and powdery mildew is much more problematic.

Successful disease management usually results from the integration of several methods of disease control. The use of resistant rootstocks and scions, fungicides, bactericides, biological control agents, environmental modification and site selection are some of the means used to control apple diseases. The precise combination and order of control measures are usually disease-specific.

18.2 Diseases Caused by Bacteria (Table 18.2)

Fire blight, blister spot, blister bark, crown gall and hairy root are diseases of apple caused by bacteria. Fire blight is the most important of these diseases and is described in more detail below. Blister spot, caused by *Pseudomonas syringae* pv. *papulans* (Rose) Dhanvantari, occurs in North America and Europe. It causes a fruit spot on 'Mutsu', 'Crispin', 'Fuji', 'Redcord', 'Sun Crisp', 'Smoothee' and a few other cultivars.

Blister bark has been described from South Africa but the pathogen *P. s.* pv. *syringae* van Hall is found as a common epiphyte on apple foliage worldwide. Crown gall and hairy root are soil-borne diseases caused by two species of *Agrobacterium*; crown gall is the most common of the two problems.

In areas where these bacterial pathogens either are not established or are rare, bacterial diseases are often avoided by planting pathogen-free nursery stock. Where these diseases are established, they are managed through orchard sanitation, wound minimization, the use of resistant rootstocks and cultivars, site selection, cultural practices that promote air movement and drying of plant surfaces and, in some cases, the use of copper and antibiotic sprays.

18.2.1 Fire blight

Fire blight is of major concern in all countries where apples are grown including countries that are currently free of this disease (Vanneste, 2000). When fire blight is epidemic, it can cause serious tree loss in nurseries and orchards (Plate 18.1), even leading to orchard removal. In high-risk areas, fire blight is limiting the planting of some highly susceptible apple cultivars and rootstocks. Strict quarantines and restrictions are maintained in countries where the disease does not currently occur; enforcing quarantine regulations and restrictions and, if necessary, eradicating the disease are very costly.

The fire blight pathogen kills fruit-bearing spurs, branches and entire trees. Infected blossoms are initially water-soaked and darker green; spurs with infected blossoms turn brown to dark brown and collapse after 4–5 days. Infected shoots turn brown to black from the tip and bend near the tip to resemble a shepherd's crook (Plate 18.2). When shoots are invaded from the base, the basal leaves and stem turn brown to black. Leaves may exhibit discoloration of the midrib, followed shortly by a darkening of the lateral veins and surrounding tissues. Bark on infected branches and scaffold limbs is darker than normal. When the outer bark is peeled away, the inner tissues are

Table 18.1. Fungal diseases of apples, names of the asexual and sexual stages of the causal fungi and their reproductive stages, the symptoms and damage most likely to be encountered and general methods of control (*Malus × domestica* Borkh.) A.L. Jones, primary collator (last update 3/12/93)

Disease (distribution ^a)	Fungal pathogen	Reproductive stage	Common symptoms ^b	Main control method
<i>Alternaria</i> blotch (A, AF, NA)	<i>Alternaria mali</i> Roberts; = <i>Alternaria alternata</i> (Fr.:Fr) Kessl apple pathotype	Conidia/conidiophores	Leaf spots, defoliation	Fungicides, cultivar selection
<i>Alternaria</i> rot (W)	<i>Alternaria alternata</i> (Fr.:Fr) Kessl	Conidia/conidiophores	Decay of fruit	None
American brown rot (A, AF, NA, O)	<i>Monilinia fructicola</i> (G. Wint.) Honey	Conidia in sporodochia; ascospores in apothecia	Decay of fruit (P)	Avoid preharvest injury to fruit
Anthraxnose canker and bull's-eye rot (E, NA, O)	<i>Pezicula malicorticis</i> (H. Jacks.) Nannf <i>Cryptosporopsis curvispora</i> (Peck) Gremmen in Boerema & Gremmen [anamorph]	Conidia in acervuli; ascospores in apothecia	Cankers on wood, decay of fruit (P)	Fungicides
Apple scab (W)	<i>Venturia inaequalis</i> (Cooke) G. Wint. <i>Spilocaea pomi</i> Fr.:Fr [anamorph]	Ascospores in pseudothecia; conidia/conidiophores	Leaf spots, scabs on fruit, defoliation	Sanitation, fungicides, resistant cultivars
Apple ring rot and canker (A)	<i>Botryosphaeria berengeriana</i> De Not. (syn <i>Physalospora piricola</i> Nose)	Conidia in pycnidia; ascospores in pseudothecia	Cankers on wood, decay of fruit	Fungicides
<i>Armillaria</i> (shoestring) root rot (W)	<i>Armillaria mellea</i> (Vahl Fr.) P. Kumm.	Basidiospores in basidiocarps (mushrooms); rhizomorphs	Decay of roots	None, avoid problem sites
Bitter rot (W)	<i>Glomerella cingulata</i> (Stoneman) Spauld & H. Schrenk <i>Colletotrichum gloeosporioides</i> (Penz.) Penz. & Sacc. in Penz. [anamorph] <i>Colletotrichum acutatum</i> J.H. Simmons	Conidia in acervuli; ascospores in perithecia	Decay of fruit	Fungicides, sanitation
Black pox (NA)	<i>Helminthosporium papulosum</i> Berg.	Conidia/conidiophores	Spots on fruit and leaves	Fungicides
Black root rot (NA for <i>X. mali</i> ; W)	<i>Xylaria mali</i> Fromme <i>Xylaria polymorpha</i> (Pers.:Fr.) Grev.	Ascospores in perithecia	Decay of roots	None
Black rot, frog-eye leaf spot and canker (AF, E, NA, SA, O)	<i>Botryosphaeria obtusa</i> (Schwein.) Shoemaker <i>Sphaeropsis malorum</i> Berk. [anamorph]	Conidia in pycnidia; ascospores in pseudothecia	Spots on leaves and fruit, defoliation, cankers on wood	Sanitation, fungicides
Blister canker (nail-head canker) (NA)	<i>Biscogniauxia marginata</i> (Fr.) Pouzar = <i>Nummularia discreta</i> (Schwein.) Tul. & C. Tul.	Conidia in a sclerotia-like stroma; ascospores in perithecia	Cankers on branches	Removal of infected branches

Continued

Table 18.1. Continued.

Disease (distribution ^a)	Fungal pathogen	Reproductive stage	Common symptoms ^b	Main control method
Blotch (NA)	<i>Phyllosticta solitaria</i> Ellis & Everh.	Conidia in pycnidia	Blotches on fruit, leaf spots, blisters in bark	Fungicides
Blue mould (W)	<i>Penicillium</i> spp. <i>P. expansum</i> Link	Conidia/conidophores	Decay of fruit (P)	Packing-house sanitation, fungicides
Brooks fruit spot (NA)	<i>Mycosphaerella pomii</i> (Pass.) Lindau <i>Cylindrosporium pomii</i> C. Brooks [anamorph]	Conidia/conidophores; ascospores in pseudothecia	Spots on fruit, often at calyx end	Fungicides
Brown-rot blossom blight (A, AF, E, NA, SA)	<i>Monilinia laxa</i> (Aderh. & Ruhl.) Honey	Conidia in sporodochia	Blighting of blossoms, spur dieback	Fungicides
Calyx-end rot (NA)	<i>Sclerotinia sclerotiorum</i> (Lib.) de Bary	Ascospores in apothecium	Decay of fruit	None
<i>Clitocybe</i> root rot (NA)	<i>Armillaria tabescens</i> (Scop.) Dennis et al = <i>Clitocybe tabescens</i> (Scop.) Bres.	Basidiospores in basidiocarps	Decay of roots	None
<i>Diaporthe</i> canker (A)	<i>Diaporthe tanakae</i> Kobayashi & Sakuma <i>Phomopsis tanakae</i> Kobayashi & Sakuma [anamorph]	Conidia (α and β spores) in pycnidia; ascospores in perithecia	Cankers on 1- and 2-year-old shoots	Sanitation
<i>Diplodia</i> canker (E, NA, O)	<i>Botryosphaeria stevensii</i> Shoemaker = <i>Physalospora malorum</i> Shear et al <i>Diplodia mutila</i> (Fr.: Fr.) Mont. [anamorph]	Pycnidia and pseudothecia; often in the same stroma	Cankers on branches	Pruning out of infected branches
European brown rot (A, E, AF)	<i>Monilinia fructigena</i> Honey in Whetzel <i>Monilia fructigena</i> Pers.: Fr. [anamorph] <i>Monilinia laxa</i> (Aderhold & Ruhland) Honey	Conidia in sporodochia, ascospores in apothecia	Blossoms and spur blight, decay of injured fruit	Sanitation, fungicides
Fish-eye rot (A, E, NA)	<i>Butlerella eustacei</i> Weresub & Illman = <i>Corticium centrifugum</i> (Lév.) Bres.	Basidiomycete, may produce basidiospores in culture	Decay of fruit (P)	None
Fly-speck (W)	<i>Schizothyrium pomii</i> (Mont.: Fr.) Arx <i>Zygophiala jamaicensis</i> E. Mason [anamorph]	Conidia in pycnidia	Small, superficial, dark spots on fruit	Cultural practices, fungicides
<i>Glomerella</i> leaf spot (NA, SA)	<i>Glomerella cingulata</i> (Stoneman) Spauld. & H. Schrenk <i>Colletotrichum gloeosporioides</i> (Penz.) Penz. & Sacc. in Penz. [anamorph]	Conidia in acervuli, ascospores in perithecia	Spots on leaves, defoliation	Fungicides

Grey-mould rot (W) – dry-eye rot, blossom-end rot <i>Leptosphaeria</i> canker and fruit rot (W)	<i>Botrytis cinerea</i> Pers. Fr. <i>Botryotinia fuckeliana</i> (de Bary) Whetzel [teleomorph] <i>Diapleelia coniothyrium</i> (Fuckel) Barr = <i>Leptosphaeria coniothyrium</i> (Fuckel) Sacc. <i>Coniothyrium fuckelii</i> Sacc. [anamorph]	Conidia and sclerotia (rare in nature)	Decay often at calyx end of fruit; nest rot of fruit in storage (P) Leaves	Packing-house sanitation and fungicides
<i>Leucostoma</i> canker and dieback (E, NA)	<i>Leucostoma cincta</i> (Fr. Fr.) Hohn <i>Cytospora cincta</i> Sacc. [anamorph] <i>Valsa auerswaldii</i> Nitschke = <i>Leucostoma auerswaldii</i> (Nitschke) Hohn. <i>Cytospora personata</i> Fr. [anamorph]	Perithecial stroma with a central pycnidium	Cankers on branches	Removal of affected branches
<i>Marssonina</i> blotch (A, NA, E)	<i>Diplocarpon mali</i> Harada & Sawamura <i>Marssonina coronana</i> (Ellis & J.J. Davis) J.J. Davis [anamorph]	Ascospores in apothecia; conidia in acervuli	Leaf spots, defoliation, spots on surface of fruit	Sanitation, fungicides
Mouldy core and core rot (W)	<i>Alternaria</i> spp.; <i>Stemphylium</i> spp.; <i>Cladosporium</i> spp.; <i>Ulocladium</i> spp. <i>Epicoccum</i> spp.; <i>Coniothyrium</i> spp. and <i>Pleospora herbarum</i> (Pers.) Rabenh wet core rot, mainly <i>Penicillium</i> spp	Conidia of various types	Discoloration and decay around the fruit core	Packing-house sanitation
<i>Monilia</i> leaf blight (A)	<i>Monilinia mali</i> (Takahashi) Whetzel <i>Monilia</i> spp. [anamorph]	Ascospores in apothecia; conidia with disjunctors	Blossom and spur blight, decay of young fruit	Sanitation and chemical control
<i>Monochaetia</i> twig canker (NA)	<i>Seindium unicorn</i> (Cooke & Ellis) Sutton = <i>Monochaetia mali</i> (Ellis & Everh.) Sacc. <i>Lepteutypa cupressi</i> (Nattras et al.) H.J. Swart [teleomorph]		Cankers in wounds on small twigs	None
<i>Mucor</i> rot (AF, NA, O)	<i>Mucor</i> spp. <i>M. piriformis</i> E. Fischer	Sporangiospores and zygospores	Soft, watery decay of fruit (P)	Packing-house sanitation
<i>Nectria</i> canker (A, AF, NA, SA, O)	<i>Nectria galligena</i> Bres. in Strass. <i>Cylindrocarpon heteronemum</i> (Berk. & Broome) Wol. in web. [anamorph]	Conidia on phialides; ascospores in perithecia	Cankers on branches, occasional fruit decay	Fungicides
<i>Nectria</i> twig blight – coral spot (E, O, NA)	<i>Nectria cinnabarina</i> (Tode Fr.) Fr <i>Tubercularia vulgaris</i> Tode Fr. [anamorph]	Conidia on sporodochia; ascospores in perithecia	Cankers on branches and trunk	Removal of affected branches

Continued

Table 18.1. Continued.

Disease (distribution ^a)	Fungal pathogen	Reproductive stage	Common symptoms ^b	Main control method
<i>Peniophora</i> root canker (O)	<i>Peniophora sacrata</i> G.H. Cunn.	Basidiomycete with crust-like fruiting-bodies	Infected roots with characteristic cracks	Resistant rootstocks and sanitation
Perennial canker (NA)	<i>Neofabrae perennans</i> Kenholz <i>Cryptosporopsis perennans</i> (Zeller & Chiridis) Wollenweb. [anamorph]	Conidia in acervuli; ascospores in apothecia	Cankers on branches, decay of fruit	Sanitation, fungicides
<i>Phomopsis</i> canker, fruit decay and rough bark (A, E, NA)	<i>Phomopsis mali</i> Roberts <i>Diaporthe perniciosus</i> Em. Marchal [teleomorph]	Conidia (α and β spores) in pycnidia, ascospores in perithecia	Cankers on wood, fruit decay (P)	None
<i>Phymatotrichum</i> root rot = cotton root rot (NA)	<i>Phymatotrichopsis omnivora</i> (Duggar) Hennebert = <i>Phymatotrichum omnivorum</i> Duggar	Hyphae with conidia on conidiophores and sclerotia	Decay of roots	None
<i>Phytophthora</i> crown, collar and root rot; (sprinkler rot) (W)	<i>Phytophthora</i> spp. <i>P. cactorum</i> (Lebert & Cohn) J. Schröt. <i>P. cambivora</i> (Petr.) Buisman <i>P. cryptogea</i> Pethybr. & Lafferty <i>P. megasperma</i> Drechs. <i>P. syringae</i> (Kleb.) Kleb.	Zoospores produced in sporangia from hyphae or germinating oospores or chlamydospores	Decay of crown and root tissues	Cultural practices, host resistance, chemical treatment
<i>Phytophthora</i> fruit rot (E, NA)	<i>Phytophthora cactorum</i> (Lebert & Cohn) J. Schröt.; <i>Phytophthora syringae</i> (Kleb.) Kleb.	See above	Rotting of fruit	Late-season fungicide sprays or postharvest treatments
Pink mould rot (W)	<i>Trichothecium roseum</i> (Pers.) Fr. Link = <i>Cephalothecium roseum</i> Corda	Conidia	Decay of fruit (P)	Prevented by refrigerated cold storage
Powdery mildew (W)	<i>Podosphaera leucotricha</i> (Ellis & Everh.) E.S. Salmon	Conidia/conidiophore; ascospores in cleistothecia	Powdery spots on leaves, fruit russeting	Cultivar selection, fungicides
<i>Rosellinia</i> root rot (W) = <i>Dematophora</i> root rot	<i>Rosellinia necatrix</i> Prill <i>Dematophora necatrix</i> R. Hartig [anamorph]	Ascospores in perithecia; pycnidia on synnemata	Decay of roots	Cultural practices, solarization
Rust, American hawthorne (NA)	<i>Gymnosporangium globosum</i> (Farl.) Farl.	Pycnia and aecidia on apple; teliospores in telial horns on cedar	Leaves	Removal of alternative host, fungicides
Rust, cedar apple (NA)	<i>Gymnosporangium juniper-virginianae</i> Schwein.	Pycnia and aecidia on apple; teliospores in telial horns on cedar	Spots on leaves, defoliation and distortion of fruit	Removal of alternative host, fungicides

Rust, Japanese apple (A)	<i>Gymnosporangium yamadai</i> Miyabe ex Yamada	Pycnia and aecidia on apple; teliospores in telia on <i>Juniperus chinensis</i>	Leaves	Removal of alternate host, fungicides
Rust, Pacific Coast pear (NA)	<i>Gymnosporangium libocedri</i> (C. Henn.) F. Kern	Aecidia on apple; teliospores in telia on <i>Libocedrus decurrens</i>		
Rust, quince (NA)	<i>Gymnosporangium clavipes</i> (Cooke & Peck) Cooke & Peck in Peck	Pycnia and aecidia on apple; teliospores in telia on cedar	Distortion of fruit	Removal of alternative host, fungicides
Side rot (E, NA)	<i>Phialophora malorum</i> (M. N. Kidd & A. Beaumont) McCulloch	Conidia at the apex of phialides	Decay of fruit (P)	Cultural practices, postharvest treatments
Silver leaf (W)	<i>Chondrostereum purpureum</i> (Pers.:Fr.) Pouzar	Basidiospores	Wood decay	Cultural practices
Sooty-blotch complex (W)	<i>Peltaster fructicola</i> (Johnson, Sutton, Hodges); <i>Geastrum polystigmatis</i> Batista & M.L. Farr; <i>Leptodontium elatus</i> (G. Mangenot) (De Hoog); and <i>Gloeodes pomigena</i> (Schwein.) Colby	Conidia in pycnidia	Blotches of various size on the surface of fruit	Cultural practices and fungicides
Southern blight (AF, NA, SA)	<i>Sclerotium rolfsii</i> Sacc. <i>Athelia rolfsii</i> (Curzi) Tu & Kimbrough [teleomorph]	Sclerotia	Decay at base of trunk	Cultural practices
Thread blight = <i>Hypochnus</i> leaf blight (NA)	<i>Corticium stevensii</i> Burt = <i>Pellicularia koleroga</i> Cooke = <i>Hypochnus ochroleucus</i> Noack	Rhizomorphs and sclerotia; basidia with basidiospores	Blighting of branches	Fungicides
Valsa canker (A)	<i>Valsa ceratosperma</i> (Tode:Fr.) Maire <i>Cytospora sacculus</i> (Schwein.) Gvritschvili [anamorph]	Pycnidia and perithecia in a stroma	Cankers on branches	Sanitation
Violet root rot (O)	<i>Helicobasidium mompa</i> Tanaka	Basidiospores in basidiocarps	Root decay	Soil sterilization
White root rot (NA)	<i>Scytinostroma galactinum</i> (Fr.) Donk = <i>Corticium galactinum</i> (Fr.) Burt	Basidia on a resupinate hymenium	Decay of roots	None
White rot (AF, NA, SA, O)	<i>Botryosphaeria dothidea</i> (Moug.) Ces. & De Not <i>Fusicoccum aesculi</i> Corda [anamorph]	Conidia in pycnidia, ascospores in pseudothecia	Decay of fruit, cankers on limbs and twigs	Fungicides and sanitation
Zonate leaf spot (A)	<i>Cristulariella moricola</i> (Hino) Redhead <i>Grovesinia pyramidalis</i> M. Cline et al. [teleomorph]	Ascospores in apothecia; conidia	Leaf spot, defoliation	Sanitation

^aApproximate geographical distribution of the disease: A, Asia; AF, Africa; E, Europe; NA, North America; O, Oceania; SA, South America; W, worldwide.

^bP, postharvest disease problem

Table 18.2. Bacterial diseases of apple, scientific name of the pathogen, symptoms and main control method.

Disease (distribution ^a)	Pathogen	Common symptoms	Main control method
Fire blight (E, NA, New Zealand)	<i>Erwinia amylovora</i>	Blight, cankers, dead trees	Resistant cultivars and rootstocks, sanitation, antibiotics
Bister spot (E, NA)	<i>Pseudomonas syringae</i> pv. <i>papulans</i> (Rose) Dhanvantari	Spots on fruit	Avoiding susceptible cultivars, antibiotics
Bister bark (AF)	<i>Pseudomonas syringae</i> pv. <i>syringae</i> van Hall	Terminal dieback, blossom blight,	None
Crown gall (W)	<i>Agrobacterium tumefaciens</i> (E. F. Smith & Townsend) Conn	Galls on roots	Sanitation, biocontrol but often less effective than on <i>Prunus</i> species
Hairy root (W)	<i>Agrobacterium rhizogenes</i> (Riker <i>et al.</i>) Conn	Excessive production of fibrous roots	Sanitation

^aApproximate geographical distribution of the pathogen. A, Africa; E, Europe; NA, North America, W, worldwide.

water-soaked with reddish streaks when first invaded; later the tissues are brown. As lesion expansion slows, the bark sometimes cracks, delineating a canker. Infected fruit develop a brown-to-black decay. During wet, humid weather, droplets of whitish to reddish-brown, sticky liquid (known as ooze) seeps from the surface of infected tissues (Plate 18.3). Infected rootstocks may show bleeding or ooze from rootstock tissue early in summer and internal necrosis of the bark and the leaves of the scion turn reddish early in the autumn.

Fire blight is caused by *Erwinia amylovora* (Burrill) Winslow *et al.*, a Gram-negative, rod-shaped, non-fluorescent bacterium with peritrichous flagella. More than 130 species in 39 genera of the *Rosaceae* are hosts. Important hosts include apple, pear, ornamental *Pyrus* and *Malus* species, quince (*Cydonia oblonga*), loquat (*Eriobotrya japonica*), hawthorn (*Crataegus* spp.), *Cotoneaster* spp., *Sorbus* spp., *Pyracantha* spp. and *Rubus* spp. Most strains of *E. amylovora* from *Rubus* do not infect apple and are therefore considered to be pathologically distinct. Primary isolation of the bacteria is by culturing on Luria-Bertani (LB) agar or some semi-selective medium. They are distinguished from other plant pathogenic bacteria based on colony colour and morphology on MM2Cu

and LB media (see Bereswill *et al.*, 1998, for the composition of these media), pathogenicity tests performed on immature fruit, seedlings or vigorous plants, and molecular assays (Bereswill *et al.*, 1995; McManus and Jones, 1995).

The pathogen overwinters in cankers located on branches and tree trunks (Fig. 18.1). Ooze can begin to appear on the surface of these cankers at or just before the onset of bloom. Bacteria are disseminated to flowers by splashing rain and, occasionally, flies and other insects that visit both bacterial ooze and blossoms. Eventually, honey bees visit infected blossoms and pick up pollen or nectar contaminated with bacteria. Spread of bacteria from flower to flower by bees is rapid. Bacteria colonize the stigmatic surface of the pistils of healthy apple and pear flowers, resulting in epiphytic populations of bacteria (Thomson, 1986). Climatic conditions govern the rate of spread and severity of blossom blight and even the infection process itself. Temperatures between 18.3 and 30°C (accompanied by rain or high humidity during the day) favour infection. Although bacteria invade the flowers primarily through natural openings, storms containing wind-driven rain or hail are important in spreading bacteria during the summer months, which under some condi-

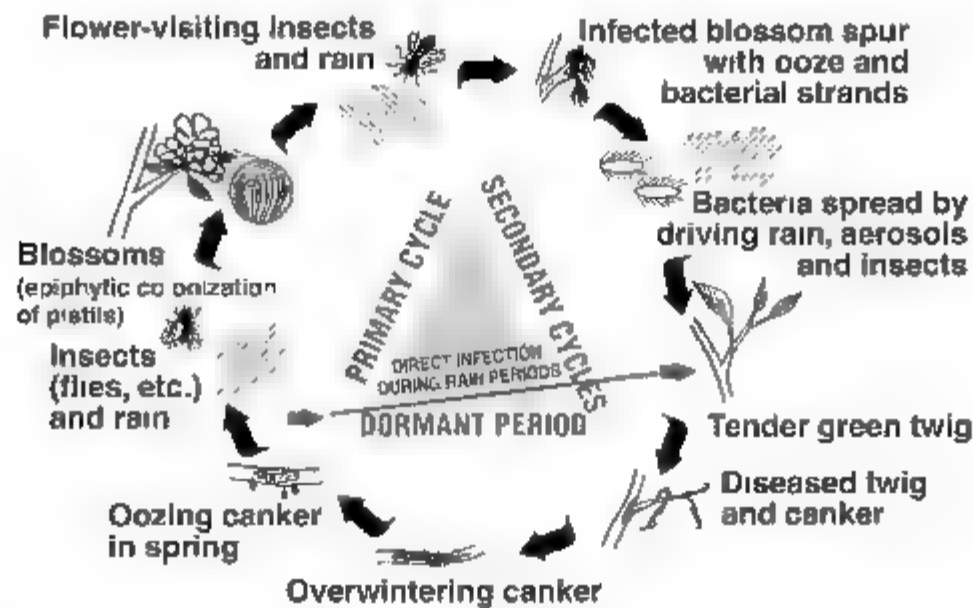


Fig. 18.1. The fire blight disease cycle. The pathogen overwinters in cankers. At the onset of bloom, bacteria begin to ooze on to the surface of cankers; splashing rain, along with flies and other insects, moves the bacteria to open flowers. Then, honey bees spread the bacteria from flower to flower on contaminated pollen and nectar. The bacteria multiply on the stigmatic surface of the pistils to produce high epiphytic populations. Favourable combinations of moisture and temperature govern infection of the flowers. Summer storms with wind-driven rain spread the bacteria, leading to sudden and severe outbreaks of diseases. Inoculum for secondary infection originates from droplets of ooze produced on infected flowers, fruit and shoots (Figure courtesy A.L. Jones)

tions lead to sudden and severe outbreaks of disease. Inoculum for secondary infection originates from droplets of ooze produced on infected flowers, fruits and shoots.

Temperature, as measured by the accumulation of degree-days (DD), governs the rate of symptom development. Symptoms are expressed when 55 DD (base 12.5°C) are accumulated following the infection date. The susceptible rootstocks M.9 and M.26 are infected by systemic movement of bacteria through symptomless scion tissue or through infected rootstock shoots (Momol *et al.*, 1998). Although the rootstock Bud.9 is blight-susceptible, rootstock blight has not developed on many Bud.9/scion combinations. Losses from rootstock blight can be avoided by using resistant rootstocks, such as G.16, G.30, G.65 and other blight-resistant rootstocks from the US Department of Agriculture–Agricultural Research Service (USDA–ARS)/Cornell apple-rootstock programme.

Many practices help to prevent or reduce the severity of fire blight. In countries where *E. amylovora* is not established, only trees produced in fire-blight-free regions should be used when establishing new orchards. These countries may already have strict quarantines

to prevent the importation of plant material that may harbour the pathogen.

In countries where fire blight is a problem, sanitation – the removal of infected portions of the tree – is critical to the success of other control measures and is effective provided it is done during the early stages of an epidemic. New orchards should be planted on blight-resistant rootstocks if available. A realistic plan for controlling fire blight is needed before making large plantings of blight-susceptible cultivars. Antibiotics have been highly effective for preventing the blossom-blight stage of fire blight, but in some regions or orchards control with antibiotics is no longer possible, due to the development of streptomycin-resistant strains of *E. amylovora*. Predictive models, particularly Maryblyt and Cougarblight in the USA and Billings' integrated system and Firescreens in Europe, help growers identify potential infection periods (Billings, 2000). Such information is helpful in timing antibiotic treatment and for avoiding unnecessary treatment. Bacterial antagonists that suppress fire blight may be integrated with antibiotics to control flower infections (Stockwell *et al.*, 1996).

18.3 Diseases Caused by Fungi

Within this diverse group of plant pathogens are the causes of most apple diseases (Table 18.1). Fungi pathogenic to apple can cause root rots, leaf spots, leaf blights, blossom blights, fruit decay, fruit spots, defoliation and trunk, branch and twig cankers. The fungal diseases discussed in this chapter are caused by fungi belonging to the general taxonomic groups represented by the mushrooms (*Basidiomycetes*) and morels (*Ascomycetes*). The phylum *Oomycota* also contains the water moulds, an important group of plant pathogens formerly classified as fungi. Fungi in the ascomycete group have scientific names for the anamorph and teleomorph. The anamorph is the asexual form (also called the imperfect stage) of the fungus and produces asexual spores (such as conidia) or no asexual spores. The teleomorph is the sexual form (also called the perfect or sexual state) and produces sexual spores (ascospores) in various fruiting bodies (pseudothecia, perithecia, apothecia, etc.). These fungi generally reproduce by spores that are dispersed by air currents or splashing water. Fungal diseases are prevented or managed by using resistant cultivars and rootstocks, site selection, sanitation, cultural practices and fungicide practices. Specific management measures vary according to disease and geographical location.

18.3.1 Apple scab

Scab occurs in virtually all apple-producing regions worldwide (MacHardy, 1996). The disease is an annual threat in cool, humid regions with frequent rainfall in spring and early summer. In semiarid regions, scab is a threat in years with above-normal rainfall or in orchards where artificial wetting periods are created from the improper use of overhead irrigation.

Scab attacks the leaves and fruit throughout most of the growing season; blossoms and bud scales are attacked for short periods in spring and late summer, respectively. Symptoms first appear on the undersides of leaves, the side exposed as buds open. Later,

symptoms are found on both sides of leaves. Conidia are produced abundantly in new lesions; therefore, lesions appear as velvety brown to olive spots that turn black with age (Plate 18.4). Severe infection can cause leaves to abscise, resulting in defoliated trees. Return bloom on trees defoliated in midsummer is often reduced due to a lack of flower-bud formation the previous summer. Fruit infections resemble leaf infections when young but turn brown and corky with age (Plate 18.5). Early-season infections are often associated with the blossom end of the fruit; later they can occur anywhere on the surface. Scab infections result in uneven growth of fruit and even cracking of the skin and flesh. Rough, black circular lesions develop in cold storage on fruit infected close to harvest. The latter phase is known as pinpoint scab. Infection of blossoms and bud scales may be observed in high-inoculum orchards when infection periods occur at critical times. Lesions on blossoms and bud scales resemble those on leaves but are seldom observed because these tissues normally drop to the ground before the symptoms are well developed.

Venturia inaequalis (Cooke) G. Wint., anamorph *Spilosea pome* Fr., causes apple scab. It has one sexual cycle and a series of asexual cycles per year. Flask-shaped, ascus-bearing fruiting bodies (pseudothecia) develop in overwintering infected leaves. Pseudothecia form as a result of the interaction of two strains of opposite mating types (heterothallic fungus). Asci in pseudothecia are eight-spored. Mature ascospores are two-celled, with the upper cell shorter and wider than the lower cell, yellowish green to tan and with smooth walls. Conidia are one-celled, yellowish-olive and pointed.

From late autumn to spring, microscopic, black, pimple-like pseudothecia develop in leaves on the orchard floor (Fig. 18.2). Normally, pseudothecia contain mature ascospores when the blossom buds start to open in spring. Maturation and discharge of ascospores lasts about 5–9 weeks. When leaves on the orchard floor become wet from rain, spores are ejected into the air. Air currents carry them to the emerging tissues, where infection occurs. Young leaves and fruit are highly susceptible to infection, but their

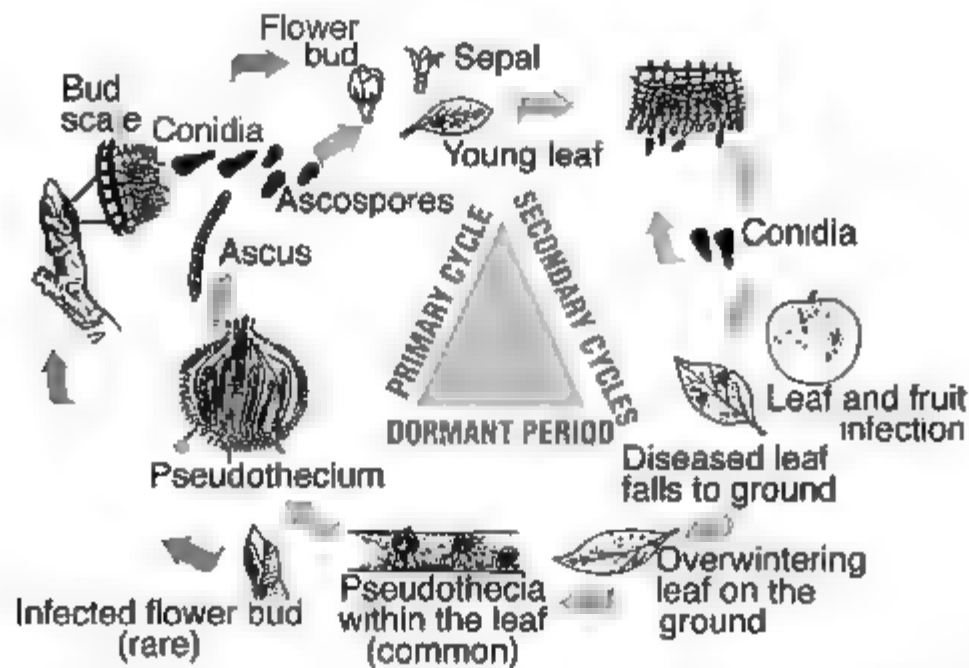


Fig. 18.2. The apple scab disease cycle. The fungus *Venturia inaequalis* overwinters in leaves on the orchard floor and sometimes in apple buds. Pseudothecia with ascospore-bearing asci in dead leaves discharge their ascospores when the leaves become wet from rain. Ascospores produce the first, or primary, infections on the young fruit and leaves. Conidia produced on the inner surface of apple-bud scales can also cause primary infections. Depending on temperature, 9–17 days are required before new scab lesions appear on the infected tissues. Conidia, formed in continual crops of new lesions, produce secondary infections. Secondary cycles are repeated many times until leaf fall in autumn. (Figure courtesy A. L. Jones.)

susceptibility declines with maturity. Spore germination begins soon after ascospores land on wet leaves or fruit. Prevailing temperatures govern the infection rate, provided a continuous film of moisture is present for germination of the spores. Depending on the average temperature after penetration, 9–17 days are required before the appearance of the olive-green, velvety scab lesions. In some apple-producing regions and on some cultivars, the fungus also overwinters in lesions on twigs and bud scales (Becker *et al.*, 1992); conidia produced in these lesions are a second form of primary inoculum. However, the number of conidia available from overwintering lesions at bud break is low compared with the number of ascospores potentially available from leaf litter.

Secondary infections are initiated by conidia produced in primary and secondary lesions. Conidia can be produced in new lesions beginning as soon as 7–9 days after infection and these lesions can produce conidia in continuous crops for several weeks. Conidial germination and infection occur under about the same conditions as germination and infection by ascospores. Secondary infection on fruit can occur in the autumn

but fails to develop until after the fruit has been held in cold storage for several months. Infections can also build up in leaves after harvest and prior to normal leaf abscission. The fungus overwinters in these leaves and they are often the source of very high levels of inoculum the following spring.

Basic studies on the biology and epidemiology of apple scab from the 1920s to the 1940s established a rational basis for scab control and these concepts continue to be refined. The initial ascosporic inoculum is usually present in large amounts; therefore, estimating the risk of the initial ascosporic inoculum and forecasts of its efficiency are very important for determining when to initiate scab-control programmes and the application frequency. Inoculum risk is determined by monitoring pseudothecia from early spring to midsummer to determine whether ascospores are mature and available for discharge and by detecting ascospore release in orchards during wetting periods. Statistical models have been developed to predict ascospore maturity based on DD accumulations and these models are replacing ascospore-monitoring programmes. Inoculum risk forecasts assume

high inoculum levels, an assumption that is usually incorrect for orchards where scab was well controlled the previous season. Therefore, methods for assessing differences in inoculum among orchards based on a potential ascospore density (PAD) system were developed (Gadoury and MacHardy, 1986). It was found that in low-inoculum orchards spray programmes in spring could be delayed until about the tight-cluster stage of bud development, rather than green tip in the normal spray schedule for high-inoculum orchards. Integrating inoculum risk with environmental risk is accomplished by the identification of 'infection periods'. Rainfall is necessary for the discharge of ascospores – free water for the germination of ascospores and penetration of tissues. The rate of this infection process is temperature-dependent, and the duration of wetness required for successful infection across a wide range of temperatures is well known (Jones, 1998). Therefore, temperature and wetness measurement can be used to forecast the success or failure of each ascospore-discharge event. These events can be monitored with environmental sensors linked to small computers placed in the orchard or with automated weather stations connected directly to computers. Fungicides with post-infection efficacy are applied after predicted but unprotected infection periods.

Apple-breeding programmes aiming for high-quality, disease-resistant cultivars are in progress in New Zealand and some European and North American countries. Over 50 scab-resistant cultivars have been released and are gaining in commercial acceptance as fruit quality and other horticultural characteristics are improved. Guarding against races of the scab pathogen that can overcome the resistance sources used by apple breeders is a high priority in these breeding programmes (Bénaouf and Parisi, 2000).

Prevention of pseudothecia formation in overwintering leaves would probably eliminate scab. Unfortunately, complete elimination of pseudothecia is not possible under orchard conditions using current methods. Spring ascospore production can be reduced by making autumn applications of urea or

fungal antagonists to the foliage just prior to leaf fall (Carisse *et al.*, 2000), but this strategy alone is not adequate for season-long scab control. This approach may be more feasible in areas with lower amounts of overwintering inoculum and mild winters.

Scab is controlled primarily with fungicides applied in predetermined schedules, beginning at green tip. The fungicides are applied on a 7–14-day interval with eight to ten applications per season. Several classes of fungicides are available for apple-scab control. They are often rotated during the season or applied as mixtures because of the high potential of the scab fungus to develop fungicide-resistant strains.

18.3.2 Powdery mildew

Powdery mildew is circumglobal and a potentially serious disease wherever apples are grown. The disease is particularly problematic in the western and mid-Atlantic regions of the USA. Severe infections reduce tree photosynthesis and transpiration (Ellis *et al.*, 1981) and may result in partial defoliation (Ogawa and English, 1991). Chronic infections can result in reduced tree vigour, poor return bloom and yield reduction. Fruit infection can result in the rejection of fruit for fresh-market sale. Apple cultivars vary in their susceptibility to powdery mildew. 'Gala', 'Braeburn', 'Ginger Gold', 'Mutsu' (Crispin), 'Cortland', 'Baldwin', 'Monroe', 'Idared', 'Honeycrisp', 'Jonathan', 'Granny Smith', 'Ginger Gold', 'Rome Beauty', 'Jonagold' and 'Pink Lady®' are particularly susceptible. 'Delicious' and 'Golden Delicious' are less susceptible.

Leaves, flowers and fruit are susceptible to infection by the powdery mildew fungus. The foliage of new terminal growth is extremely susceptible to infection. The initial signs of powdery mildew consist of white to grey felt-like patches on the lower leaf surface. These patches are comprised of masses of fungal mycelia and spores (conidia). As disease progresses, mildew signs may also appear on the upper leaf surface and eventually cover the entire leaf. Infected foliage may curl, blister and eventually

become brittle and necrotic (Plate 18.6). Internodal shortening may occur on severely infected shoots. Infected flower petals are distorted, stunted and light yellow to light green. Fruit infection typically results in stunting accompanied by the presence of a fine network of rough lines (russetting) (Plate 18.7).

Powdery mildew is caused by *Podosphaera leucotricha* (Ell. & Ev.) E.S. Salmon. The fungus is superficial on the host surface but withdraws water and nutrients from host tissue, using a structure called a haustorium. The fungus produces barrel-shaped conidia in chains, which are dispersed by air currents and initiate subsequent infections of foliage and fruit (Fig. 18.3). *P. leucotricha* survives through winter as mycelium in infected buds. This mode of perennation results in the production of 'flag shoots' (shoots covered with powdery mildew) when shoots emerge in the spring. Winter temperatures are the most important factor affecting the amount of carry-over inoculum. Temperatures colder than -12°C kill the fungal mycelium in buds; temperatures lower than -24°C may kill the infected buds (Spotts *et al.*, 1981). Conidia produced on flag shoots initiate the first spring infections and

are therefore primary inocula, which initiate additional new infections. This cycle of sporulation and foliar infection can continue as long as susceptible foliage is being produced. This secondary phase of powdery mildew can cycle many times during the growing season. Temperature is the most important factor affecting disease development. Conidia germinate at temperature between 10 and 25°C ; the optimum temperatures for germination are 20 – 22°C . The sexual stage (ascocarps) of *P. leucotricha* occasionally forms on infected twigs. Ascocarps are minute, brown to black, spherical fruiting bodies that contain eight unicellular ascospores. Various researchers have suggested that this stage is insignificant in the epidemiology of the disease. Fruits are especially susceptible to infection during the bloom period (Daines *et al.*, 1984)

Powdery-mildew epidemics are favoured by high humidity; therefore problems with mildew can often be avoided or reduced with cultural practices that promote air movement and light penetration. On susceptible cultivars, effective disease management usually depends on a fungicide-spray programme. Benzimidazole, sulphur, horticultural mineral, oils, demethylation-inhibiting

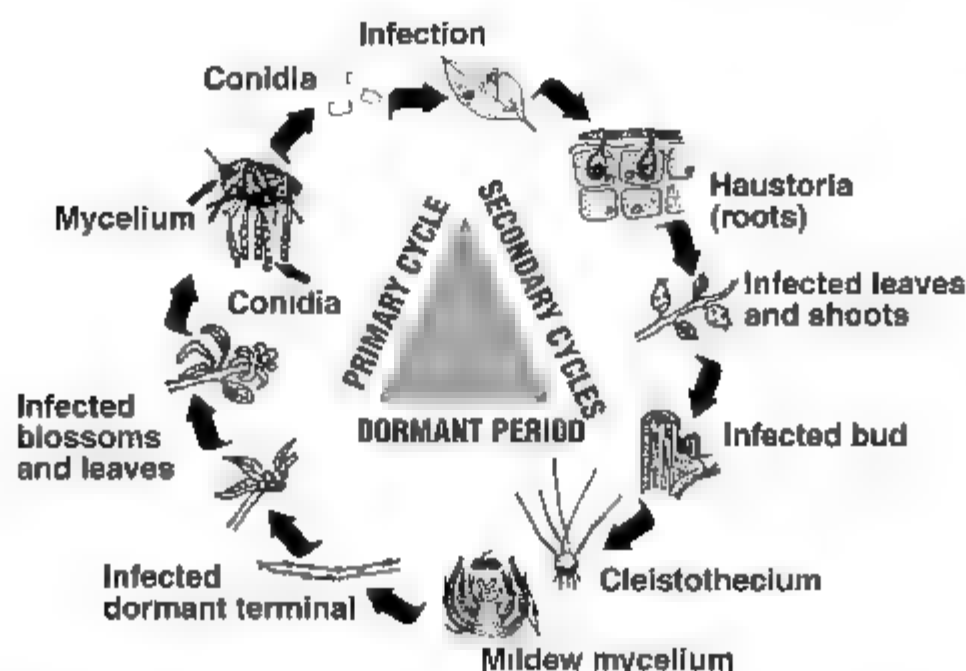


Fig. 18.3. The apple powdery mildew disease cycle. The fungus overwinters as mycelium in infected buds. Mildew conidia, produced on leaves arising from the infected buds, become wind-borne and cause primary infections on healthy leaves and fruit. Secondary infections are produced from conidia produced in both primary and other secondary infections and are repeated until shoot growth stops in late summer (Figure courtesy A.L. Jones.)

(DMI) and strobilurin fungicides are effective against powdery mildew. Spray programmes should commence at tight cluster and continue until the production of new foliage ceases. Because powdery mildews can develop resistance to benzimidazole, DMI and strobilurin fungicides, rational resistance-management strategies usually require the inclusion of two or more fungicide classes in a season-long programme. DMI fungicides applied in apple-scab-management programmes generally provide the added benefit of mildew control.

A predictive system has been developed for aid in managing infections caused by *P. leucotricha*. Podem[®] (Xu, 1999) is a system developed in the UK that simulates epidemics of secondary mildew on vegetative shoots. The effects of weather on conidial production, dispersal and germination are used to calculate a favourability index. The model itself is driven by hourly ambient temperature, relative humidity, shade temperature and the total daily duration of rainfall. The model has been incorporated into an integrated apple disease warning system (ADEM) and successfully used to time fungicide applications and in some cases has resulted in improved disease control, with a 40% reduction in fungicide usage (Berrie and Xu, 1999).

18.3.3 Brown-rot diseases

Several brown-rot fungi attack apple in different parts of the world. The species and their distribution are: *Monilinia fructicola* (Wint.) Honey in most regions except Europe, where it is a European Union-listed quarantine pest (Smith *et al.*, 1992); *Monilinia laxa* (Aderh. & Ruhl.) Honey in Asia, Europe, North and South America and South Africa; and *Monilinia fructigena* (Aderh. & Ruhl.) Honey in Europe and Asia (Byrde and Willetts, 1977). A related species, *Monilinia mali* (Takahashi) Whetzel, causes *Monilia* leaf blight of apple in Asia.

The brown-rot fungi cause blossom wilt, spur dieback, cankering and fruit rot (Plate 18.8); the incidence and severity of these symptoms depend on the species of

pathogen present. *M. laxa* causes blossom blight, spur dieback and cankering of branches; *M. fructigena* causes fruit rot and sometimes cankers when the fungus spreads into branches from the fruit; and *M. fructicola* causes a fruit rot. *Monilia* leaf blight infects young apple leaves; mycelium invading from leaves kills flower clusters, young fruits and fruiting spurs.

The species of *Monilinia* can be differentiated by microscopic observation of conidia formed in chains in culture or on infected tissue. *M. mali* can be differentiated by disjunctors present within the conidial chains. *M. fructicola*, *M. fructigena* and *M. laxa* can be differentiated based on cultural characteristics, isozyme variation, vegetative interactions and PCR assays.

The life cycles of these pathogens differ only in the role that the perfect stage (apothecia) plays in the overwintering of the fungi. *M. mali* and occasionally *M. fructicola* produce apothecia on mummified fruit on the ground. All species overwinter in infected parts of the tree. Secondary spread is by conidia produced on infected host tissue within the tree and on trees of neighbouring hosts, particularly *Prunus* species.

Losses due to fruit decay caused by *M. fructigena* and *M. fructicola* increase gradually up to harvest time and are usually associated with injuries to the fruit. Cultivars prone to fruit cracking, such as 'Cox's Orange Pippin' and 'James Grieve', are especially susceptible to infection. Infection also occurs through wounds caused by birds pecking at fruit, insects infesting fruit and hail. Fruit decay is prevented by avoiding cultivars prone to fruit cracking, by limiting the damage caused by birds and other wounding agents and by orchard sanitation methods aimed at reducing the build-up of inoculum.

Blossom infections from *M. laxa*, *M. fructigena* and *Monilia* leaf blight are controlled by orchard sanitation, combined with the application of fungicides. Blighted spurs and cankers are removed and destroyed during the dormant period and in the growing season. Fungicides applied as the flowers begin to open and one or two times 5–7 days later should prevent blossom blight.

18.3.4 Summer diseases

Summer diseases refer to a collection of nine diseases that tend to be most severe from 2–3 weeks after petal fall until harvest. They are most prevalent in warm and moist growing regions of the world, where they can cause extensive losses if not controlled. They are relatively minor problems in arid and cooler growing regions.

Of all the summer diseases, rot diseases are most destructive and can cause losses of 50% or more if not controlled. These diseases tend to be most severe in the south-eastern USA but cause problems in other areas as well. The life cycles of the pathogens that cause these diseases are similar, as is the overall strategy for managing them.

18.3.4.1 Bitter rot

Bitter rot is the most destructive of the three rot diseases and is the most difficult of the three to control once an epidemic has begun. It is caused by *Colletotrichum gloeosporioides* (Penz.) & Sacc. in Penz. and *Colletotrichum acutatum* J.H. Simmons. These pathogens coexist in many orchards, whereas in others one or the other species predominates. *Glomerella cingulata* (Stoneman) Spauld & H. Shrenk is often listed as the sexual stage of *C. gloeosporioides* but may be a distinct taxon (Shane and Sutton, 1981a; TeBeest *et al.*, 1997).

The *Colletotrichum* spp. that cause bitter rot survive from one growing season to another in mummified apples, twig cankers and other dead wood in the tree. In the late spring when temperatures begin to warm, conidia are released, initiating infections on fruit. Fruit is susceptible throughout the season (Shane and Sutton, 1981b; Noe and Starkey, 1982). Lesions begin as small, circular, light tan to brown spots, sometimes surrounded by a red halo. As the lesions enlarge, they become brown and sunken (Plate 18 9) and extend into the flesh of the apple in a V-shaped pattern, which is a good diagnostic technique. Fruiting structures on the surface of the lesion, called aecidia, produce copious amounts of salmon-coloured conidia, which can be splash-dispersed to other fruit, initiating new infections. Consequently, the disease

has enormous potential for secondary spread and is very difficult to control when the weather is warm and wet.

G. cingulata also survives from year to year on dead wood and mummified apples. There appear to be several strains, which produce somewhat different symptoms. A serious leaf-spot disease, *Glomerella* leaf spot, occurs on 'Gala' in Brazil, which is associated with *G. cingulata* (Sutton and Sanhueza, 1998). It causes small irregular lesions 3–12 mm in diameter on leaves and can result in significant defoliation when severe. It also causes small corky lesions on fruit. This strain overwinters in leaves on the orchard floor, much like apple scab, and infection is initiated in the late spring by airborne ascospores, which are discharged during periods of rain. Perennation also occurs in twig cankers and mummified apples. *Glomerella* leaf spot has been observed in the south-eastern USA (Gonzalez and Sutton, 1999). Another strain of *G. cingulata* produces a large, firm, brown lesion on the fruit, which is not sunken, and few spores are produced on the surface of the lesion (Shane and Sutton, 1981b). It is not known whether this strain causes a leaf-spot symptom.

Management of bitter rot is based on sanitation and a preventive spray programme. In warm, rainy, growing regions, the disease cannot be successfully managed without pruning to remove inoculum sources and facilitate drying in the tree canopy. Current-season fire blight strikes need to be removed because they can be colonized by the bitter-rot fungi and serve as an inoculum source late in the season. The ethylenebisdithiocarbamate (EBDC) fungicides are most effective, but restrictions on their application after petal fall in the USA have limited their usefulness. Captan, ziram and thiram (applied on a 10–14-day schedule from petal fall to harvest) are the most effective fungicides currently registered in the USA. The benzimidazole fungicides are ineffective.

18.3.4.2. Black rot and bot (white) rot

Black rot and bot rot are caused by *Botryosphaeria obtusa* (Schwein.) Shoemaker and *Botryosphaeria dothidea* (Moug.) Ces. &

DeNot., respectively. Although caused by the same fungal genus, the diseases caused by the two species are different in many ways. Both overwinter in dead wood, mummified apples and cankers in the tree canopy and produce ascospores and conidia through most of the growing season. Both cause a fruit rot and cankers, but only *B. obtusa* causes a leaf spot. Infections by *B. obtusa* can begin as early as silver tip and occur throughout the season, whereas infections by *B. dothidea* occur mainly during the warm summer months. *B. obtusa* infections develop into firm brown lesions on the fruit and *B. dothidea* infections develop into light brown, soft, watery rots

B. obtusa infections can occur on the sepals as soon as the buds begin to open. These infections spread into the fruit as they begin to mature, resulting in a firm brown rot on the calyx end (Plate 18.10). Other fruit infections can occur from soon after petal fall until harvest during favourable weather (Arauz and Sutton, 1989). Infections that occur soon after petal fall first appear as small, dark pimples. As lesions enlarge, they become dark and irregular in shape and are often surrounded by a red halo. Eventually the entire fruit may become rotten and shrivel, remaining attached to the tree. Leaf spots (known as frog-eye leaf spot) begin as small purple to brown necrotic lesions, which enlarge to 4–5 mm in diameter and are often surrounded by a purple halo. When infections are numerous, leaves may turn yellow and abscise.

B. dothidea infections can occur from soon after petal fall until harvest (Parker and Sutton, 1993). Infections that occur early in the season often remain quiescent and do not begin developing until the soluble solids in the fruit begin increasing. This often leads growers to think that their late-season spray programme is ineffective, when in actuality the disease increase that they are observing is more closely related to their spray programme earlier in the season. As lesions begin to develop on the fruit, they extend in a cylindrical manner towards the core. Once the core is invaded, the entire apple becomes infected. Rotten fruit are often light tan in colour and are very soft

and mushy (Plate 18.11). Under cooler temperatures, the rot tends to be darker in colour and firmer, making it more difficult to separate from black rot. Infected fruit may fall or may remain attached to the tree and mummify

Control of the black rot and bot rot is based on sanitation and preventive fungicide sprays. Colonized dead wood and mummified apples can both serve as inoculum sources. Wood infected by the fire blight pathogen can become colonized by these fungi and produce spores during the current growing season. This wood should be removed during the early summer. Prunings should be chopped by a flail mower or pushed out of the orchard and burned. Fungicides should be applied every 10–14 days from petal fall to harvest. Captan and the benzimidazole fungicides are most effective; the dithiocarbamate fungicides are not especially efficacious

18.3.4.3 Sooty blotch and fly-speck

Sooty blotch and fly-speck are two of the most common diseases in humid growing areas. While they do not reduce yield, affected fruit are usually downgraded from fresh-market to processing or juice grades. Sooty blotch is a disease complex caused by several fungi and is characterized by dusty to dark colonies of fungi growing epiphytically on the surface of the fruit (Williamson and Sutton, 2000; Plate 18.12). They range from small discreet colonies to large, amorphous ones. Each colony has a characteristic appearance, depending on the fungus involved. Fly-speck colonies are characterized by numerous thyrothecia, which are scattered throughout the thallus, giving it an appearance of 'fly-specks' (Plate 18.13). Colonies range from several to many millimetres in diameter

Sooty blotch is a disease complex caused by *Peltaster fructicola* Johnson, Sutton & Hodges, *Leptodontium elatius* (G. Mangenot) De Hoog, *Geastrumia polystigmatis* Batista & M.L. Farr and probably other fungi. These fungi grow superficially on the cuticle of affected fruit. All have numerous reservoir hosts in the wooded areas in close proximity

to orchards and most inoculum comes from outside the orchard. Conidia of *P. fructicola* and *G. polystigmatis* are primarily water-borne and are spread by wind-blown rain; conidia of *L. elatius* are airborne. Infection can occur as early as several weeks after petal fall. Symptom expression is closely associated with the hours of wetting that occur in the spring. Brown and Sutton (1995) found that the first symptoms of sooty blotch (and fly-speck) appeared after an average of 273 h of leaf wetting of 4 h duration or greater accumulated following the first rain which occurs 10 days after petal fall. *P. fructicola*, *G. polystigmatis* and *L. elatius* all produce conidia on fruit, which serve as secondary inoculum. All apple cultivars are equally susceptible, but the colonies are more visible on light-skinned cultivars. Washing and brushing in the packing line can often remove small colonies with lightly pigmented thalli.

Fly-speck is caused by *Schizothyrium pomi* (Mont.: Fr.) Arx (anamorph *Zygophiala jamaicensis* E. Mason). Ascospores of *S. pomi*, which are produced in thyrothecia on reservoir hosts, provide the primary inoculum for infections. While some infections occur on fruit, the most important infections occur on reservoir hosts, which serve as a source of inoculum (conidia) throughout the growing season. Moisture and temperature requirements for colony development are similar to those of the fungi causing sooty blotch. While the fungi that cause sooty blotch grow superficially on the cuticle, *Z. jamaicensis* metabolizes the cuticle and the incipient thyrothecia become firmly attached to it, making the colonies difficult to remove during washing and brushing in the packing line. There are no differences in susceptibility among cultivars to either fly-speck or sooty blotch.

Control of sooty blotch and fly-speck is based on sanitation to remove reservoir hosts, pruning to open the canopy and facilitate drying, thinning fruit clusters to improve drying, and fungicide sprays. The benzimidazole and dithiocarbamate fungicides are most effective; captan is not very effective. The benzimidazole fungicides have some eradicant activity against the diseases. Brown and Sutton (1995) developed a model

for timing sprays of benzimidazole fungicides to manage sooty blotch and fly-speck. They found that sprays of benzimidazoles could be omitted in the cover-spray programme until 225 h of wetting had accumulated. In dry years, using the model could save three to five spray applications. Rosenberger (Agnello *et al.*, 1999) and Hartman and Smigell (Hartman, 1995; Smigell and Hartman, 1998) have modified this model for their growing regions.

18.3.4.4 Brooks fruit spot

Brooks fruit spot caused by *Mycosphaerella pomi* (Pass.) Lindau affects apples primarily in the south-eastern and mid-Atlantic apple-growing regions of the USA (Sutton *et al.*, 1987). Symptoms on fruit appear as small, slightly sunken, superficial lesions on the fruit (Plate 18.14). Lesions resemble cork spot, but there is no corky tissue beneath them. Leaf spots appear as small purple flecks on leaves (Plate 18.15). Affected fruit are often downgraded from fresh-market to processing or juice grades.

M. pomi overwinters in apple leaves and ascospores are discharged from pseudothecia during rainfall. The ascospores are produced during a distinct period, about 6 weeks in duration, beginning about 2 weeks after petal fall (Sutton *et al.*, 1987). Symptoms do not appear on fruit and leaves until 6–8 weeks after infection. There is no secondary spread. There are some differences among cultivars; 'Golden Delicious', 'Rome Beauty', 'Stayman' and 'Idared' are quite susceptible; 'Delicious' is relatively resistant. A preventive fungicide program that includes a dithiocarbamate or benzimidazole fungicide controls the disease.

18.3.4.5 Alternaria blotch

Alternaria blotch, caused by *Alternaria mali* Roberts (= *Alternaria alternata* apple pathotype), was first reported in the USA in the late 1980s (Filajdic and Sutton, 1991). The disease affects 'Delicious' and cultivars with 'Delicious' as a parent (e.g. 'Empire') and is characterized by circular, necrotic spots on the leaves (Plate 18.16), which, when abun-

dant, can cause extensive defoliation. Defoliation by the fungus is exacerbated by mite injury. *A. mali* and the European red mite act synergistically to increase defoliation (Filajdic *et al.*, 1995). When defoliation is extensive, fruit size and soluble solids are reduced. Fruit symptoms are usually limited to small, corky, dark lesions, often associated with the lenticels.

The fungus overwinters in leaves on the orchard floor and to a lesser extent in leaf buds. Infection by airborne conidia occurs within a month of petal fall if temperature and moisture conditions are favourable. The numerous secondary cycles that can occur throughout the growing season may result in extensive defoliation.

Control of the disease is based primarily on preventive control of mites to minimize defoliation. Most fungicides currently registered for apples in the USA, with the exception of the strobilurins, have little effect on *Alternaria* blotch.

18.3.4.6 Black pox

Black pox, caused by *Helminthosporium papulosum* Berg., is a problem, especially on 'Golden Delicious' in the south-eastern USA. It is characterized by small, black, slightly sunken lesions, 3–9 mm in diameter on the fruit (Plate 18.17). Leaf spots begin as red haloes with light green centres, enlarge to 1.5–11.0 mm and turn tan to brown with purple borders (Taylor, 1963). *H. papulosum* overwinters in twig lesions. Conidia produced in these lesions initiate infections during the summer. Black pox is one of the least-studied summer diseases, and conditions favouring infection are not known. Preventive fungicide sprays of dithiocarbamate or benzimidazole fungicides provide effective control.

18.3.4.7 Necrotic leaf blotch of 'Golden Delicious'

Necrotic leaf blotch is a physiological disorder that affects primarily 'Golden Delicious' and its progeny (Sutton and Sanhueza, 1998) and is a particular problem on the new cultivar 'Pacific Rose'. It is characterized by the sudden appearance of large, irregular

lesions, often bounded by veins. Mid-shoot leaves are most severely affected. Lesions are initially pale green, over a few hours turn chocolate brown and, as they age, often appear tan (Plate 18.18). Severely affected leaves turn yellow in a few days and abscise. The disorder appears following periods of cloudy, cool weather during the summer and can result in 50% or more defoliation. It has been associated with an increase in the production of gibberellins, which is triggered by environmental factors. Necrotic leaf blotch can be controlled by applications of heavy metal-containing fungicides, such as ziram, thiram, mancozeb and Bordeaux, or foliar nutrient sprays (e.g. zinc oxide).

18.3.5 *Phytophthora* crown and root rot

Phytophthora crown and root rot is a potentially serious soil-borne disease wherever apples are grown. The disease is prevalent when susceptible rootstocks are planted in heavy soils or in areas of poor soil drainage. Infected trees exhibit a variety of symptoms. During summer, foliage on infected trees may appear light green. As the season progresses, leaves on infected trees turn a reddish-bronze. Branches on infected trees typically have stunted leaves and poor terminal growth. Fruit on infected trees is smaller than normal and colours prematurely. Accurate diagnosis of *Phytophthora* crown and root rot frequently requires digging in order to expose the upper portions of the root system. Infected tissue is reddish brown and delineated from healthy tissue by a definite margin (Plate 18.19). Diseased trees are often randomly distributed throughout a planting. The disease is sometimes confused with the rootstock phase of fire blight.

The *Phytophthora* species present, soil moisture and temperature, relative resistance of the rootstock and contamination of nursery stock all affect the incidence and severity of the disease (Welsh, 1942; Sewell and Wilson, 1959; Browne, 1984; Jeffers and Aldwinckle, 1986; Ogawa and English, 1991). The disease can result from infection by any of several species in the genus *Phytophthora*: *P. cactorum*,

P. cryptogea, *P. cambivora*, *P. megasperma*, *P. syringae*, *P. citricola* and *P. drechsleri*. These fungi can persist in soil for extended periods of time as thick-walled sexual spores, called oospores. When soil becomes saturated and temperatures are conducive for sporulation, oospores germinate to produce sporangia. Within sporangia are numerous unicellular motile spores that are liberated into the soil water. The spores, known as zoospores, swim short distances in the soil pore spaces or can be transported longer distances by runoff or irrigation water. When zoospores contact roots of susceptible hosts, they germinate and establish new infections. Zoospores are liberated only when soil is saturated. Prolonged flooding favours the production of sporangia and dissemination of zoospores and may also predispose the host to infection. The majority of new infections are initiated between the pink stage of blossom development and the beginning of shoot elongation. The optimum temperature for disease development depends upon the *Phytophthora* species present, but in general soil temperatures between 20 and 30°C favour the disease.

Phytophthora crown and root rot is managed through the integration of chemical and cultural practices. Two of the most important decisions of the producer are to plant pathogen-free nursery stock and to avoid the use of susceptible rootstocks. Rootstocks vary in their susceptibility to the various species of *Phytophthora*. The vast majority of rootstock-susceptibility evaluations have been conducted using *P. cactorum*. The MM.104 and MM.106 rootstocks are particularly susceptible to the disease, while M.9 is relatively resistant. During planting, orchard managers should ensure that the graft union is not in contact with soil. Heavy or poorly drained soils should be avoided. In irrigated areas, water should be managed to avoid prolonged flooding and the presence of standing water around the base of trees. Plantings are sometimes established on raised beds in order to facilitate drainage around the base of trees. Acylalanine and ethyl phosphonate fungicides available for control of this disease are applied as soil drenches or foliar sprays, respectively (Jeffers and Wilcox, 1990)

18.3.6 European or *Nectria* canker

Nectria or European canker is circumglobal in distribution and particularly problematic in northern Europe and parts of South America (Grove, 1990). The disease is considered minor in most of North America, but can be a serious problem in the production areas of coastal California. The disease is characterized by zonate cankers located on the main trunk or scaffold limbs (Plate 18.20). Young infected tissue is darker than surrounding healthy tissue. Limb or tree death can occur from girdling, which results from canker enlargement. A layer of callus tissue is formed annually around each canker. The fungus invades callus tissue and spreads to healthy tissue outside the callus layer. Over a period of years this results in cankers with characteristic zonate appearances. In some areas nurseries are important sources of infected trees.

The disease is caused by *Nectria galligena* Bres. The fungus produces ascospores and conidia in orange-red fruiting-bodies produced in twig, branch or trunk cankers. Spores are produced in a gelatinous matrix and dispersed by the impaction of water droplets. The disease can be aggravated by over-the-canopy irrigation. Infection occurs through leaf scars and pruning wounds. *Nectria* canker is favoured by cool, moist weather.

An integrated approach is required for successful disease management. Diseased wood should be removed from the orchard and destroyed. Young infected trees should be severely pruned or removed. In some areas diseased bark is removed to prevent spore production. Copper fungicides (e.g. Bordeaux mixture) are sometimes applied prior to autumn rains in order to protect leaf scars.

18.4 Postharvest Diseases

Apples are also host to a multitude of postharvest diseases and disorders. The former are caused exclusively by pathogenic fungi. Two of the more serious postharvest diseases are blue mould and grey mould, which are the first and second most important postharvest diseases of apple, respec-

tively. Most postharvest pathogens invade fruit wounded during harvest, shipping or handling. Therefore, the management of postharvest diseases begins with very careful fruit harvest, bin sanitation and transport. Fruit bins used for transport should be free of soil, leaves and rotten fruit debris. Fruit should be picked individually and placed very gently into bins. Orchard access roads should be smooth and free of ruts and major bumps. Bins should be transported at speeds that will not result in shifting or bouncing. Additional means of postharvest disease management include packing-house sanitation, rapid immediate postharvest cooling, fungicide drenches and the provision of adequate tree nutrition.

18.4.1 Blue mould

Blue mould, which is caused by fungi in the genus *Penicillium*, is the most common postharvest disease of apple (Rosenberger, 1990; Plate 18.21). Decayed flesh is soft and watery and separates readily from healthy tissue. Infected epidermal tissue is light to dark brown. Infected fruit are malodorous. The causal organism produces blue or blue-green conidia on the surface of infected fruit. *Penicillium* spp. are present in orchard soils and on decayed fruit in the orchard and packing-house and in postharvest drench solutions and flume water. Fruit infection typically occurs through wounds. Wounding should be prevented during harvest, shipping and processing. Infested fruit bins and warehouses should be disinfested before processing fruit.

18.5 Diseases Caused by Viruses, Viroids, Phytoplasmas and Other Virus-like Agents

Viruses or virus-like agents incite over 50 described diseases of apple. These agents include viruses, viroids and phytoplasmas and several graft-transmissible agents that have yet to be identified. Some of these diseases have great economic consequences in that they are associated with fruit deformi-

ties or severe tree decline and even death. The degree of affliction depends greatly on the rootstock and scion selection, pathogen isolate and climate. Viruses or virus-like agents that incite severe symptoms on some apple selections will cause no obvious symptoms on others. However, even in the latter case, significant yield reductions have been documented in the few studies undertaken to study such effects (van Oosten, 1983). Thus, infections by viruses and virus-like agents are important to the commercial production of apples.

Although most of these agents do not spread naturally, many are common in commercial orchards. The universal presence of many of these agents is due to collecting grafting material from infected but apparently symptomless trees while preparing for vegetative propagation of new trees. The propagation of trees from infected sources ultimately affects yield and, under certain environmental circumstances or clone combinations, results in orchards that are not economically productive due to fruit-quality issues or tree decline. The only reasonable method for controlling these diseases is the initial use of virus-tested propagation materials.

Quick and reliable diagnostic assays are available for a few of the viruses and virus-like agents that infect apple. However, for the most part, detection of such infections is a cumbersome and laborious proposition. Furthermore, only a few of the agents that incite these diseases have been identified. The use of modern laboratory diagnosis is precluded until such identifications are made. Most assays for these agents are conducted by inoculative assays on sensitive woody indicator selections; these tests require 2 months to 3 years to complete.

Aetiological studies of viruses that infect woody plants are greatly enhanced if the virus is first transmitted to a herbaceous host. Unfortunately, many of the virus-like agents that elicit disease in apple trees have not been successfully transmitted to herbaceous plants and therefore are called 'non-sap-transmissible'. This may simply mean that the correct combinations of host plants and transfer conditions have not yet been

found. The significance of this limitation is that progress towards characterization of these pathogens has been dramatically slowed. Nevertheless, the non-sap-transmissible viruses of fruit trees present a very interesting and challenging group of viruses, since relatively little is known about them. Contemporary methods in molecular biology have accelerated investigation of these pathogens.

Pathogens are frequently referred to as viruses based on the ability to transmit the pathogen by grafting and/or budding and the absence of any other obvious pathogens. This simplistic distinction is often incorrect. Many disease-causing agents are more correctly referred to as 'virus-like' agents since no direct association between a pathogen and disease has been established – that is, Koch's postulates have not been fulfilled.

The disease names commonly used in the literature are descriptive of the disease and host but provide little information about the pathogen. Consequently, a pathogen or variant thereof may be associated with different disease names, depending on the symptom produced, the latter frequently affected by cultivar and environment. With advances in our ability to isolate and characterize fruit-tree pathogens at the molecular level, this complicated structure of nomenclature is evolving to reflect more accurately the nature of the pathogen, rather than the symptoms that they elicit. This is of practical as well as academic importance. By relating a pathogen to other members of a group that

share many important qualities, we may be able to predict the behaviour of that pathogen based on the epidemiology of a few well-studied pathogens in the same group.

The list of apple diseases caused by 'virus-like' agents is alarming in its length. However, many of these disease names were applied locally to a particular symptom and thus many of the names are duplicative. Also, many of these diseases have very limited distribution. Only diseases that remain of a more general importance will be discussed in detail. For an expanded list of reported diseases of apple that are induced by virus-like agents, see Németh (1986).

18.5.1 Chlorotic leaf spot

Relatively few well-characterized viruses are routinely found in the *Malus* of commerce (Table 18.3). Each of these viruses incites disease with major characteristics on selected host cultivars that help identify the disease agent.

The causal agent apple chlorotic leaf-spot trichovirus (ACLSV) is one of the most widely distributed viruses of fruit trees. Although first described as a virus in apples, it was subsequently found to be very widespread in stone fruits, where it can cause severe losses in production. Although the interaction of ACLSV with many commercial apple cultivars is latent, it was first discovered associated with the

Table 18.3. Diseases of apple with known virus aetiology and their vectors.

Disease	Causal agent	Known means of transmission
Apple chlorotic leaf spot	Apple chlorotic leaf-spot trichovirus	Grafting
Apple decline (on Virginia crab)	Apple stem-grooving capillovirus	Grafting
Apple mosaic	Apple mosaic ilarvirus	Grafting
Apple mosaic (Tulare)	Tulare apple-mosaic ilarvirus	Grafting
Apple stem grooving	Apple stem-grooving capillovirus	Grafting
Apple stem pitting	Apple stem-pitting foveavirus	Grafting
Apple union necrosis	Tomato ringspot nepovirus	Nematodes and grafting
Fiat apple	Cherry rasp-leaf nepovirus	Nematodes and grafting
Spy decline	Apple stem pitting foveavirus	Grafting

decline and death of new *Malus* breeding lines in an apple-scab-resistance breeding programme. Over the past few decades, there have been several examples where the interaction of the virus with specific rootstocks is not latent. The top-working disease of Japan is believed to be a hypersensitive reaction of rootstocks (*Malus prunifolia* var. *ringo*) to isolates of ACLSV found in contaminated apple scions from North America. This resulted in significant failure of mature trees (reviewed in Mink, 1989). The death of cells at the graft union results in weakened trees with reduced vigour and productivity and which are very susceptible to wind damage.

ACLSV is diagnosed by serological testing, indexing on herbaceous hosts (*Chenopodium quinoa*) or budding to *Malus* indicator species, usually *Malus sylvestris* cv. R12740-7A (also known as 'Russian'). In the latter case, chlorotic leaf symptoms appear soon after new leaves develop unless the ambient temperature rises above 20°C. Low virus titre and inhibitors in *Malus* often limit the use of serology or indexing on herbaceous plants. Molecular techniques of diagnosis, such as RT-PCR, are becoming more common methods of diagnosis (Kummert *et al.*, 1995; Kinard *et al.*, 1996). The extreme strain variation of ACLSV has limited the widespread acceptance of serological and molecular methods

18.5.2 Apple decline (on 'Virginia Crab')

Infection of most apple trees with apple stem-grooving capillovirus (ASGV) is latent – that is, there are no acute symptoms visible. However, when infected scion material is grafted on to sensitive rootstocks, such as *M. sylvestris* cv. 'Virginia Crab', growth and development of the 'Virginia Crab' wood cylinder is impaired and deep grooves appear under the bark. The vascular tissue of the 'Virginia Crab' often becomes necrotic, resulting in weakness and a visible brown line at the graft union. The trees often break at this necrotic union (Németh, 1986). Stem grooving caused by ASGV is not seen on current commercial apple

cultivars, but appears on rootstocks with crab apple in their heritage.

ASGV can be diagnosed by herbaceous indexing on *C. quinoa*, although this method is not very reliable. Woody indexing on *Malus micromalus* GMAL273.a or *M. sylvestris* cv. 'Virginia Crab' (Howell *et al.*, 1995) or detection by RT-PCR is the preferred method of testing (Kummert *et al.*, 1995; Kinard *et al.*, 1996)

18.5.3 Flat apple

This disease is caused by cherry rasp-leaf nepovirus (CRLV) (Parish, 1977), a virus that is believed to be native to western North America, ranging from Utah to southern British Columbia. CRLV is believed to have originated in one or two species of native vegetation and subsequently been transmitted into horticulturally important crop plants, such as apple and cherry. The symptoms in apple are most striking on the fruit of 'Red Delicious' and related cultivars. The length of the fruit is significantly reduced to produce a fruit that is squat, and the stem cavity is almost absent (Plate 18.22). At first, only a few fruit will be affected, but eventually the entire tree will be involved.

CRLV is transmitted by the nematode *Xiphinema americanum* (*sensu lato*) (Wagnon *et al.*, 1968). Therefore, secondary spread of the disease is relatively slow. Apple trees planted on sites previously planted to rasp-leaf-diseased cherry trees can become infected. In addition to fruit trees, many orchard weeds, such as dandelions and plantains, are hosts, although they exhibit no symptoms of the disease. This makes elimination of the virus from an infected orchard very difficult. The alternative hosts and/or the nematode vectors would have to be eliminated to protect replanted trees.

Since CRLV achieves high concentration in young shoots, it can be readily detected by serology and by mechanical inoculation of *C. quinoa* with extracts from young leaves in early spring. Leaf symptoms and tip necrosis on *C. quinoa* usually develop 3 days after inoculation.

18.5.4 Apple mosaic

Apple mosaic ilarvirus (ApMV) induces dramatic white bands or patterns on leaves of many apple cultivars (Plate 18.23). Affected leaves may have irregular distribution through the tree or even on individual limbs. The severity of the symptoms can vary dramatically from year to year, with symptoms being almost undetectable in seasons with high temperatures during the growing season. This disease can result in significant production losses (ranging up to 40%) depending on the cultivar, virus isolate and environment (Posnette and Cropley, 1956).

ApMV is detected by serological assays but results (when apple tissue is tested) are variable. Therefore, serological testing is best limited to confirming the identity of the pathogen in herbaceous indexing. ApMV can also be detected by inoculating field-grown trees of 'Golden Delicious' apple. Herbaceous indexing on *C. quinoa* is possible but quite unreliable. Molecular methods of detection, such as RT-PCR (Rowhani *et al.*, 1995), are becoming more widely accepted, as the methods are evaluated with more and varied isolates of the virus.

18.5.5 Stem pitting

The viral nature of apple stem pitting was discovered soon after the Second World War in mid-western North America (Guengerich and Millikan, 1956). Production of crab apples had become uneconomic and old crab apple rootstocks were budded over to standard cultivars, such as 'Delicious'. Two or three years after budding, the crab apple rootstocks became pitted and severely weakened. This is an example where the 'latent' virus in the 'Delicious' scion resulted in significant economic damage when the variety was budded on to rootstocks with crab apple in their heritage. Apple stem-pitting foveavirus (ASPV), the causal agent of apple stem-pitting disease, is thought to have been distributed worldwide in contaminated apple and pear propagation material.

Woody indexing on any one of a variety of *Malus* species is the method most frequently

used to detect ASPV. Epinasty and decline may be observed after 1 year when 'Spy227' is the recipient. 'Radiant' crab apple is a more reliable detection host. It is sensitive to a wide range of ASPV isolates and displays severe epinasty and decline within 6 weeks under controlled greenhouse conditions. The development of stem-pitting symptoms on 'Virginia Crab' is also reliable, but at least two growing seasons are required for trustworthy results. Fruit with ridges and flutes are produced if the 'Virginia Crab' is allowed to bear. Molecular methods are also available for the detection of ASPV. RT-PCR (Nemchinov *et al.*, 1998) is sensitive and offers faster diagnosis relative to woody indexing.

18.5.6 Union necrosis

Union necrosis is caused by tomato ringspot nepovirus (TmRSV) (Stouffer and Uyemoto, 1976). Symptoms of infection generally do not appear until the tree reaches bearing age, at which time the tree assumes an unthrifty growth habit. The leaves and bark are reddish in colour, and bloom and fruit set are abnormally high. Depending on the rootstock/scion combination, the results of infection may range from very mild to a rapid decline in tree health, resulting in death. In severe reactions ('Red Delicious' on MM.106), the union of rootstock and scion will reveal a dark necrotic line spanning the union, with soft, spongy, orange bark flanking the union. This disease is common in several locales along the east coast of North America, and has been reported sporadically in the Pacific Northwest of the USA. TmRSV is transmitted by dagger nematodes, *X. americanum* (*sensu lato*), which are abundant in eastern fruit-growing areas of North America (Stouffer and Powell, 1989). Other species belonging to this nematode group, *Xiphinema revesi* and *Xiphinema californicum*, are also known to be vectors of TmRSV in orchards.

TmRSV is easily transmitted from young leaves to *C. quinoa* by mechanical inoculation with crude extracts. *Prunus tomentosa* is a diagnostic woody host for this virus. Alternatively, serological and RT-PCR (Griesbach, 1995) assays can be used to detect it.

18.6 Diseases Caused by Phytoplasmas

(Table 18.4)

18.6.1 Proliferation

Apple proliferation occurs throughout much of Europe, but has not been reported in the western hemisphere. The disease is caused by an apple proliferation phytoplasma. The pattern of occurrence in European orchards suggests that the pathogen is harboured in the native weed population, from which it moves into the orchards. The vector of this pathogen is at least one species of leafhopper, *Fieberiella floru*. This disease reduces fruit size by up to 30–70% and fruit have longer than normal peduncles. However, the most striking symptom, for which the disease is named, is the proliferation of vegetative shoots, otherwise known as witches'-broom. In addition, apple leaves exhibit greatly enlarged stipules. Because the disease is debilitating and insect-vectored, apple proliferation disease has important quarantine significance in the western hemisphere.

The most widely accepted detection method for apple proliferation phytoplasma has been woody indexing in the field. Bark patches from roots of the test plant are budded on to 'Golden Delicious' and the tree is observed for 2 years for the appearance of witches'-broom and the enlarged stipules. However, the long observation period and concern about reliable transmission of the pathogen encouraged the development of alternative detection methods. Detection by PCR (Lorenz *et al.*, 1995) is becoming widely accepted and the techniques are becoming increasingly refined to improve the reliability of molecular methods (Carraro *et al.*, 1998; Skrzeczkowski *et al.*, 2001). PCR is now the preferred test method.

18.6.2 Chat fruit

Apple chat fruit is believed to be caused by phytoplasma infection. Sensitive cultivars develop undersized fruit, many of which drop in June. The remaining fruit do not develop colour properly and may exhibit dark water-soaked spots. Many of the current commercial cultivars do not express any symptoms of apple chat fruit. The pathogen is detected by budding on to 'Lord Lambourne'. An incubation period of up to 3 years is required for reliable detection. Until a firm association of a biological agent with apple chat-fruit disease can be established, the use of biological indicators remains the only means of detection.

18.7 Diseases of Apple Caused by Viroids

(Table 18.5)

Viroids are sub-virus particles that are difficult to detect. Since proteins are not part of their structure, serological methods are not useful. Woody indexing and molecular detection methods are commonly used to diagnose these pathogens.

18.7.1 Blister bark

Apple blister bark is characterized by areas of the bark taking on the appearance of orange tissue-paper. The disease can be induced by apple fruit-crinkle viroid (AFCVd) (Ito *et al.*, 1993). As the underlying tissue becomes desiccated, the bark cracks and peels. Scarring of the underlying tissue occurs. Several mineral deficiencies can mimic infection by AFCVd, so proper diagnosis is important.

Table 18.4. Diseases of apple suspected to be caused by phytoplasma.

Disease	Causal agent	Known means of transmission
Apple chat fruit	Phytoplasma	Grafting
Apple proliferation	Apple-proliferation phytoplasma	Leafhoppers and grafting

Table 18.5. Diseases of apple known to be caused by viroids

Disease	Causal agent	Known means of transmission
Apple blister bark	Apple fruit-crinkle viroid (AFCVd)	Grafting
Apple dimple fruit	Apple dimple-fruit viroid (ADFVd)	Grafting
Apple fruit crinkle	Apple fruit-crinkle viroid (AFCVd)	Grafting
Apple scar skin	Apple scar-skin viroid (ASSVd)	Grafting
Dapple apple	Apple scar-skin viroid (ASSVd)	Grafting

18.7.2 Dapple apple

Dapple apple aptly describes one of the diseases caused by apple scar-skin viroid (ASSVd). Affected fruit, especially near the calyx end, bear small circular spots, which enlarge and increasingly contrast with the background colour as the fruit matures (Plate 18.24). Larger spots may coalesce to produce dappling or a broad zone of discoloration. There are no pronounced leaf or bark symptoms. Since many commercial cultivars do not express symptoms, this disease has been particularly problematic when old orchards are top-worked to change cultivars. The original cultivar may not express symptoms, whereas the new cultivar does. Pear also appears to be a symptomless carrier of ASSVd; the role of pear as a symptomless carrier of this pathogen in apple-disease aetiology is unknown. 'Stark's Earliest' ('Scarlet Pimpernel') or 'Delicious' can be used for woody indexing, and three crops must be observed for accurate assessment of viroid status. 'Scarlet Pimpernel' grown at 18°C under constant light for 2 months will yield diagnostic symptoms on its foliage (Skrzeczowski *et al.*, 1993). Molecular techniques are preferred for their speed and reliability. Both RT-PCR (Hadidi and Yang, 1990) and hybridization (Hadidi *et al.*, 1991) assays are used for ASSVd.

Apple scar-skin disease is a more severe disease caused by ASSVd, as compared with the milder one referred to as dapple apple. Symptoms usually begin at the distal portion of the fruit and the severity increases as the fruit matures. Small discoloured circles merge to form large green-brown to brown patches (Plate 18.25). Eventually, the brown patches become necrotic and fissures appear on the fruit. Diseased fruit are significantly smaller

than fruit from uninfected trees. Diagnosis is performed as described for dapple-apple disease. The dapple and scar-skin diseases evoked by ASSVd appear to be dependent upon climatic and cultivar differences. The original isolates of each produce similar diseases on fruiting trees of 'Scarlet Pimpernel' (W.E. Howell, Washington State University, unpublished data).

18.7.3 Dimple fruit

Apple dimple fruit caused by apple dimple-fruit viroid (ADFVd) has been observed in several commercial cultivars of southern Italy (DiSerio *et al.*, 1996). The disease induces depressions on the fruit surface as it matures. Under the depression will be an area of necrotic tissue.

18.7.4 Fruit crinkle

Apple fruit-crinkle disease is caused by isolates of AFCVd (Ito *et al.*, 1993). The viroid was described in Japan, where fruit symptoms are most severe on the cultivar 'Ohrin'. This pathogen can be detected by woody indexing on the apple cultivars 'Delicious' or, preferably, 'NY5822', where it induces symptoms of blister bark (Ito *et al.*, 1993).

18.8 'Virus-like' or Graft-transmissible Diseases of Apple with No Known Causal Agents (Table 18.6)

There are many diseases of apple for which no pathogen has been identified. The disease

Table 18.6. Graft-transmissible diseases of apple for which there are no known causal agents ^a

Apple blister bark	Apple green crinkle	Apple ringspot
Apple dead spur	Apple horseshoe wound	Apple rosette
Apple decline	Apple internal bark necrosis	Apple rough skin
Apple false sting	Apple leaf pucker	Apple rubbery wood
Apple flat limb	Apple ring russet	Apple pustule canker
Apple freckle scurf	Apple ring-line pattern	

^aThere are many more described but rare graft-transmissible diseases of apple (Németh, 1986)

names are generally descriptive of the symptoms. Some may be caused by pathogens described above but, until more information is obtained about their aetiology, the causal agents remain an enigma. Since the agents for these diseases have not been identified, confirmation of the pathogen depends on symptom expression on susceptible cultivars. All are graft-transmissible. Furthermore, as most of these diseases are spread primarily through the use of infected propagation material, the creation of virus-certification programmes over the past 40 years has essentially eliminated many of these diseases from commercial apple production. Still a few continue to cause concern.

18.8.1 Green crinkle

Apple green-crinkle disease, a severely debilitating disease of some apple cultivars, is always associated with trees infected with ASGV, ASPV and ACLSV. The individual viruses have not been separated to determine if this disease symptom is induced by a mixture of viruses, by a particular isolate of one of the viruses or by another as yet uncharacterized pathogen. Apple green-crinkle disease is diagnosed by woody indexing on the apple indicator 'Golden Delicious'. The trees are observed for the development of fruit symptoms during the following three crops. Symptoms begin to appear after the fruit reaches 1.2 cm in diameter. Fruits develop deep depressions and distortions, which become more severe as the fruits mature. Cracks may develop in pits and crevices (Plate 18.26). Depressions are linked through the flesh to the vascular system by discoloured tissue. Severe fruit symptoms

may appear on only one or two limbs of an infected tree, and there are no acute foliar symptoms associated with the disease (Thomsen, 1989). Budding and grafting of contaminated propagation material is the major mechanism by which apple green-crinkle disease is spread. If field spread occurs, it is very slow and possibly by root grafting only.

18.8.2 Rubbery wood

Apple rubbery wood affects 2-year-old wood of apple and pear trees. On sensitive cultivars, branches develop that are very pliable and droop under their own weights (Waterworth and Fridlund, 1989). Affected limbs are also very sensitive to cold and frost damage. The disease originated in Europe and was later introduced to North America with infected rootstock. Many older rootstocks introduced from Europe were uniformly infected with rubbery wood. In countries with active certification programmes, this disease has become increasingly rare. The degree of symptom development is dependent on climate. The pliable limbs and poor growth are more extreme in moderate climates, relative to warmer environments. No obvious symptoms are associated with many commercial cultivars. Nevertheless, fruit yield and quality can be adversely affected (van Oosten, 1983). The pathogen has been assumed to be a phytoplasma, based on electron-microscopic examination of affected tissues, but attempts to confirm this association by molecular techniques have been contradictory (Poggi Pollini *et al.*, 1995; Bertaccini *et al.*, 1998). The disease is detected by indexing

on 'Lord Lambourne', followed by 3 years of observation for the development of limbs lacking normal lignification.

Apple flat limb is believed to be caused by the same agent that causes apple rubbery wood (see above). Apple flat limb is only observed in those areas where sensitive cultivars, such as 'Gravenstein', are grown. The disease results in flattening of the shoots and branches on limbs that are 2-3 years old and eventually leads to deep furrows that become more severe as the branches become older (Fridlund and Waterworth, 1989). In addition to reduced vigour and production, the weak limbs are susceptible to easy breaking. Severely affected limbs are also more susceptible to winter or frost damage. The disease is detected by woody indexing on 'Gravenstein' or 'Lord Lambourne', followed by 3 years of observation.

18.8.3 Dead spur

Apple dead spur was originally observed in the western USA, but has since been reported throughout North America and in Europe and Asia (Parish, 1989). The characteristic symptom is death of fruiting spurs, with the resulting development of long segments of blind wood. This is most pronounced on the interior of the tree, so the canopy in the centre of the tree is sparse, with fruiting spurs at the shoot tips. The disease is spread through the use of infected propagation material. No natural spread has been observed. The only means by which the diagnosis based on symptoms can be confirmed is bud-inoculating spur-type 'Delicious' trees. Symptoms will develop in the third or fourth year after inoculation. Since this disease is difficult to diagnose, it may be overlooked in virus-testing programmes. Like green-crinkle disease, dead spur has not been observed in the absence of ACLSV, ASPV or ASGV. Therefore, although the dead-spur agent poses a concern for the safe propagation of healthy apple trees, elimination from propagation programmes of trees with these three 'sentinel' viruses may well indicate freedom from this and other graft-transmitted diseases of unknown aetiology.

18.9 Control Measures

Very few viruses or virus-like agents of apple disease spread naturally in the orchard. This means that the most efficient and cost-effective control measure for apple virus diseases is the use of propagation material and plants that are certified to be free from viruses. Once the trees are planted in the orchard, they should, for the most part, remain virus-free. Still, some spread of these pathogens occurs in orchards via tree-to-tree root grafts. Such root grafts provide effective means by which pathogens can move from an infected tree to the next. However, this process is relatively slow and involves spread only to adjacent trees. Thus, if a diseased tree is detected in an established orchard, it may be prudent to remove adjacent trees to eliminate the virus.

In those cases where some form of natural field transmission exists, diseases can be much more difficult to control. Again, initial planting of certified virus-free material is the first step in maintaining a healthy orchard. In European countries, where apple proliferation phytoplasma is prevalent, regular insecticide applications to control the leafhopper vector can significantly reduce the incidence of this disease (Kunze, 1976).

The two diseases of apple whose causal agents are known to be transmitted by nematodes, flat apple and union necrosis, can be very difficult to control. Exclusion of the virus initially is crucial since, once the virus is present, it is very difficult to eliminate it from an orchard. Dagger nematodes, *Xiphinema* spp., are nearly universal and difficult to eradicate. Fumigation and soil pretreatment before planting will reduce but not eliminate these nematodes from soil. Leaving the ground planted in plants that are not virus hosts for 1-2 years before replanting will help prevent transmission of these viruses to the young trees. The nematodes lose the ability to transmit these viruses with each moult. Since many weed plants common in the orchard floor, such as dandelion and plantain, act as reservoirs of these two nepoviruses, intense weed control is required during this period of fallow. If these viruses and their nematode vectors are present in an area, it is best to select rootstock/scion combinations that offer protection against the nematode and/or virus disease.

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19 Ecology and Management of Apple Arthropod Pests

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19.1 Introduction

Apples present a distinct challenge to integrated pest management (IPM), due in part to their perennial growth habit and physical complexity. The various organs of the tree's structure provide multiple habitats suitable for arthropod colonization. In one study (Oatman *et al.*, 1964), 763 species of arthropods were discovered using apple as a host plant. While many of these were transitory, perhaps 100 or so species have been consid-

ered pests at some point in time. This survey referred to one orchard in a temperate production zone in central North America, and we can only presume the total for the world is far greater. Despite this, only a dozen or so arthropods in any given region are considered serious or chronic pests. A few, such as the codling moth, the European red mite and, to a lesser extent, the two-spotted spider mite are pests virtually wherever apples are grown; others are strictly regional pests

When the pest complexes are viewed as a whole, a pattern of ecological homologues emerges. These homologues may be closely related species, or unrelated taxa that have similar feeding habits. The tetranychid mite complex in the Pacific north-west (*Tetranychus urticae* Koch, *Panonychus ulmi* (Koch) and *Tetranychus mcdanieli* McGregor) all feed in the same manner and cause a similar type of foliar damage (Beers *et al.*, 1993). The leaf-roller complex (moths in the family Tortricidae) all feed on leaves and the surface of apple fruits. Weevils (e.g. the plum curculio *Conotrachelus nenuphar* (Herbst)) and thrips (the western flower thrips, *Frankliniella occidentalis* (Pergande)) are examples of two unrelated taxa that cause similar types of damage (surface feeding and oviposition, leaving a superficial scar) and at about the same period in fruit development (during or shortly after bloom).

A number of pest species are strictly monophagous on apple (e.g. *Aphis pomi* De Geer), while others are oligophagous or even highly polyphagous (e.g. *T. urticae*). The degree of host specialization does not appear to be related to pest status. One of the key pests worldwide (codling moth, *Cydia pomonella* (L.)) is moderately oligophagous, feeding primarily on a few species of *Rosaceae* and one member (walnut) of the *Juglandaceae*. However, many species exhibit a certain degree of plasticity in their feeding behaviour and are capable of shifting hosts or expanding their host range over time. An example is the apple maggot, *Rhagoletis pomonella* Walsh, in western North America. A host shift was recently demonstrated for this species (from apple to cherry) (Jones *et al.*, 1989), even though a closely related species, *Rhagoletis indifferens* Curran, already occupied this niche in this region (Utah). Apple is an introduced crop in the majority of the areas where it is grown, so the pest complex of any given region is typically a mixture of pests from the native region that have been introduced over time (many before strict quarantine regulations were imposed) and native pests that have adapted to using apple as a host (e.g. apple maggot).

The classification of pests in this chapter is necessarily an arbitrary choice. We refer to arthropod taxa, but, for pest-management purposes, the taxon is not necessarily the most useful unit. Our approach has been more crop-centred, in that groupings have been made on the basis of damage type (Fig. 19.1), which is in turn usually highly related to its potential economic importance. Within some of the larger groups (fruit feeders), we have grouped pests by time of attack or by type of damage caused. Overarching the crop and productivity issues, we have superimposed the ecological niche and ecological homologue concepts in an attempt to make the plant herbivore relationship clearer.

19.2 Systems of Pest Management

19.2.1 Pesticide-based

The discovery and commercialization of synthetic organic pesticides in the latter half of the 20th century represented a major qualitative change in pest management. For the first time since the beginning of agriculture, producers had a broad range of highly effective and relatively inexpensive products to use for insect control (Table 19.1). Their ease of use and often long residual toxicity to pests made them very popular and, to some extent, the applications were an insurance policy against pest damage. The euphoria was short-lived, as resistance problems began developing, sometimes within a few seasons' use. The organochlorines, introduced to agriculture after the Second World War, were largely supplanted by the organophosphates, carbamates and pyrethroids within a few decades. The problems associated with the use of these products became apparent after a relatively short time, including environmental persistence and damage (especially the organochlorines), mammalian toxicity (e.g. applicator and farm-worker safety, especially the organophosphates), possible consumer effects from residues on foods (carcinogenicity, teratogenicity, mutagenicity or chronic neural effects), and destruc-

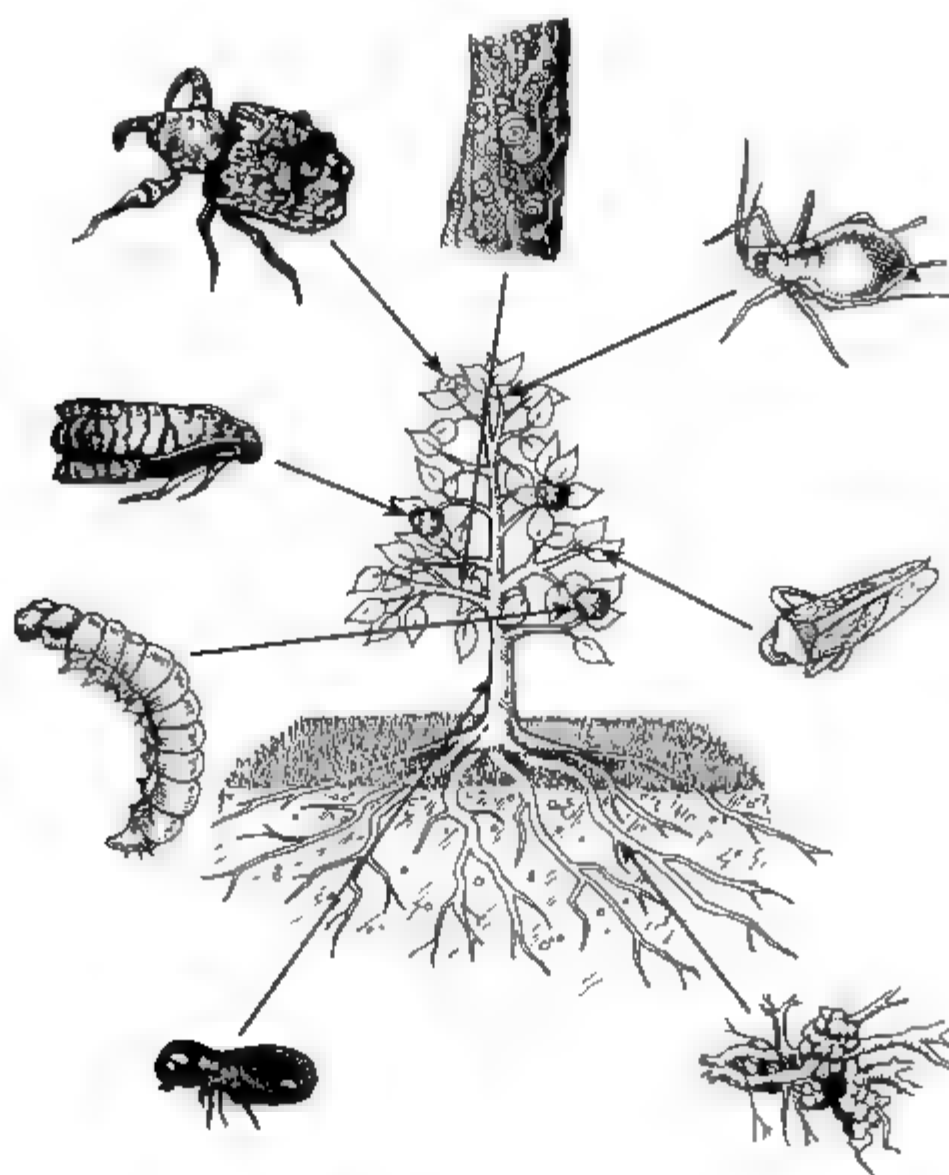


Fig. 19.1. Examples of arthropod pests attacking various parts of the tree. Clockwise from top: scale (feed on bark), aphids (phloem feeders on shoots and leaves), leafhoppers (pierce mesophyll cells and remove contents), woolly apple aphid galls (on roots), bark beetles (attack trunk and major scaffolds), leaf-rollers (feed on fruit surface and leaves), codling moth (feeds internally in fruit), plum curculio (oviposits and scars young fruitlets). (Illustration by G. Steffan.)

tion of pests' natural enemies and selection for resistant pest populations. There were clear economic benefits driving the use of these materials: 30–50% damage from codling moth in the latter part of the lead arsenate era (1940s) was common (Driggers, 1937), whereas the economic threshold for this pest today is generally set at < 1%. Despite this, the disenchantment with these materials has been growing steadily since the 1950s.

One of the side-effects of the pesticide-based era was that the bulk of entomological research was directed at the development and optimum use of the new pesticides, and basic biology and biological-control research slowed considerably. The search for alterna-

tive tactics was minimal, because of the efficacy of the new pesticides. Non-pesticidal tactics with some degree of promise were dismissed because of their relatively higher expense, lower efficacy or greater complexity of implementation. The concept of mating disruption, well established by the 1970s (Roelofs, 1979), was not registered for use on apples in North America until the early 1990s, and is still not registered in some European countries. Similarly, the sterile-insect technique, although demonstrated as feasible for codling-moth control in the 1960s (Proverbs *et al.*, 1966), was not implemented in tree fruit on a large commercial scale until the early 1990s, and then only on a limited acreage in British Columbia, Canada.

Table 19.1. Historical use of insecticides and acaricides in apple

Class/pesticide ^a	Type (I = insecticide, A = acaricide)	Use period (approximate)	Comments
Inorganic			
Lead Arsenate	I	1890s–1950s	Once the sole control measure for codling moth and other pests, this compound was used for > 50 years until resistance occurred and replacement insecticides became available. Soil residues are still present
Sulphur	I/A	Late 1800s–present day	Often applied with lime as a safener, this material is still widely used for both arthropod pests and diseases. Used in late winter or early spring, it can be phytotoxic
Cryolite	I		Used briefly during periods of codling-moth resistance; occasional use in organic production
Dinitro Compounds			
Dinitro- <i>o</i> -cresol (DNOC)	I/A	1930s–1970s	Several compounds in this group have been used, but DNOC was the most common. Highly phytotoxic; thus use was confined to dormant sprays. Used with oil to control aphid eggs and overwintering scale. No longer permitted in Europe (2000)
DN-111	A	1940s–early 1950s	A summer acaricide. Phytotoxic
Botanicals			
Neem	I	1980s–present	As a group, these were once the primary pesticides allowed in organic production; some are being withdrawn (see individual chemicals). Widely variable in terms of mammalian toxicity. Derived from the seeds of neem (tree) (<i>Azadirachta indica</i> A. Juss); has antifeedant, repellency and/or growth-regulator influence on many orders of insects
Ryania extracts (main active ingredient ryanodine)	I	1950s–present	Ground bark of a tropical shrub (<i>Ryania</i> spp.); once widely used for codling-moth control, it still has a limited place in organic apple production
Rotenone	I/A	1930s–present	A neurotoxin best known for its toxicity to fish; no longer allowed in most organic certification programmes. Component of roots of tropical plants (e.g. <i>Derris</i> spp.) Controls a wide range of arthropod pests
Pyrethrins	I/A	Ancient times to present	Several derivatives of flowers in the genus <i>Chrysanthemum</i> . Control of a wide range of insects and mites. Residues disappear very quickly. Little commercial orchard use except organic
Nicotine	I		A highly poisonous substance derived from <i>Nicotiana</i> spp., used commonly in the early part of the century for aphid and other soft-bodied insect control. Usually as nicotine sulphate

Chlorinated hydrocarbons			Generally a very persistent group of neurotoxic compounds in soil, water and animal tissues; very few still in use today for this reason. Mammalian toxicity relatively low
DDT (dichlorodiphenyltrichloroethane)	I	Mid-1940s–1970s	The most recognizable name in this class, subject of the book <i>Silent Spring</i> . Highly persistent, originally with a very broad spectrum of activity. Primary target was codling moth, but it created severe mite flare-ups. Toxic to many beneficial insects.
TDE (DDD) (dichlorodiphenyldichloroethane)	I		Physical and chemical properties similar to DDT; more effective than DDT against red-banded leaf-roller.
Benzene hexachloride (BHC)	I		Used primarily pre-bloom for aphid control; in season use could give fruit an off flavour.
Lindane	I	1940s–present	Purer gamma isomer of BHC, more widely used.
Methoxychlor	I	1940s–present	Use in tree fruit currently limited to leaf-miner control (as a premix with malathion).
Endrin	I	1960s	Limited use against Lepidoptera.
Endosulfan	I/A	1950s–present	One of the few remaining chlorinated hydrocarbon compounds still widely used (primarily in USA). Control of sucking, chewing, boring insects; some acaricidal activity, especially rust mites.
Dicofol	A	1950s–present	Related to DDT. Highly toxic to phytoseiid mites, less used currently.
DMC (dichloromethylbenzhydrol)	A	1950s	Related to DDT. Limited availability and high cost.
Ethyl dichlorobenzilate	A	1950s	Limited use due to phytotoxicity.
Organophosphates			Broad-spectrum neurotoxins introduced after Second World War, many members acutely toxic to mammals. Many were acaricidal when first used, but resistance developed after a few seasons' use. Once the most prevalent group used on tree fruits, they are gradually being replaced by new compounds.
TEPP (tetraethylpyrophosphate)	I/A		Very highly toxic to mammals, but short-lived residues. Used against aphids, mites, scales and Lepidoptera.
Azinphosmethyl	I	1950s–present	Broad-spectrum and widely used for 30–40 years; fairly high mammalian toxicity; uses currently being restricted.
Diazinon	I	1950s–present	Broad-spectrum, moderate mammalian toxicity; also available to home-owners.
Malathion	I	1950s–present	One of the lowest mammalian-toxicity compounds in this group; little used in commercial production any more. Short residual, thus preharvest use is popular.
Chlorpyrifos-ethyl	I	1960–present	Widely used for pre-bloom aphid control and post-bloom Lepidoptera control.
Chlorpyrifos-methyl	I	1960s–present	Control of various foliar pests (lepidopterous, aphids, scales).
Ethion	I	1950s–1980s	Some use pre-bloom for scale and aphids.
Carbophenothion	I/A	1950s	Somewhat phytotoxic, more limited spectrum of activity than azinphosmethyl and parathion.

Continued

Table 19.1. *Continued.*

Class/pesticide ^a	Type (I = insecticide, A = acaricide)	Use period (approximate)	Comments
Methidathion	I	1950s–present	Minor use pre-bloom against San Jose scale (USA)
Ethyl parathion	I/(A)	Late 1940s–1990s	Highly toxic, broad-spectrum and once widely used, this material was withdrawn from the market in some countries in the 1990s. Originally also acaricidal
Methyl parathion	I	1940s–1990s	Similar in toxicity and spectrum to ethyl parathion, often sold as an encapsulated formulation to prolong the residue; withdrawn from the market in the 1990s
Phosmet	I	Early 1970s–present	Moderately broad activity, similar to azinphosmethyl, but lower worker hazard
Demeton	I/(A)	Mid-1950s–late 1980s	A systemic material used primarily for aphid control. Originally acaricidal
Phorate	I/(A)	1950s	Systemic in both foliar and soil applications. Originally acaricidal. Potentially phytotoxic
Phosphamidon	I/(A)	1950s–1980s	Systemic. Widely used as an aphicide, originally acaricidal. Marginally phytotoxic
Mevinphos	I	Mid-1950s–mid-1990s	Systemic. Extreme acute oral and dermal toxicity to mammals, but short residual
			Used primarily as an aphicide, some Lepidoptera activity
Dimethoate	I/A	Late 1960s–present	Systemic. Used for aphid and <i>Lygus</i> control
Phosalone	I/A	1960s–present	Broad-spectrum pesticide. Control of Lepidoptera and Diptera
Carbamates			Neurotoxins with a slightly different mode of activity from that of the organophosphates
Carbaryl	I/A	1950s–present	Broad-spectrum insecticide, low mammalian toxicity; widely used as a fruit thinner as well as an insecticide. Some eriophyid activity, toxic to phytoseids, causing spider-mite outbreaks
Methomyl	I	1970s–present	Much higher mammalian toxicity, used primarily for control of Lepidoptera
Oxamyl	I/A	Mid-1980s–present	A more toxic carbamate, sometimes used for Lepidoptera; also toxic to both phytophagous and predatory mites
Formetanate hydrochloride	I/A	1970s–present	Effective against mites, thrips, some Hemiptera/Homoptera and Lepidoptera, toxic to predatory mites
Pinmicarb	I	1970s–present	Selective systemic insecticide used primarily as an aphicide (except USA). Low toxicity to natural enemies
Organotin			Acaricides widely used in the 1970s and 1980s; resistance problems curtailed use
Azocyclotin	A	1970s–present	Long-acting acaricide with contact action
Cyhexatin (hexakis)	A	1970s–mid-1980s	Widely used until resistance became widespread; withdrawn from the US market in 1987
Fenbutatin oxide	A	1970s–present	Similar in activity to cyhexatin, apparent cross-resistance to that compound

Pyrethroids			A group based on the activity of natural pyrethrins, but more active and with longer residual. Generally broad spectrum insecticides/acaricides with low mammalian toxicity, but famous for acute toxicity to phytoseiid mites. Useful near to harvest due to their small safe-to-harvest interval (few days)
Fenvalerate/esfenvalerate	I/A	1970s–present	Targeted Lepidoptera, but other pests also controlled (Hemiptera/Homoptera)
Permethrin	I	1970s–present	Esfenvalerate was a more active isomer of fenvalerate, replacing it in the 1980s
Acinathrin	A/I	1990s–present	Control of fruit- and leaf-eating Lepidoptera and Coleoptera
Bifenthrin	I/A	1980s–present	Mainly used as an acaricide against European red mite. Good insecticidal activity against thrips
Deltamethrin	I	1970s–present	Mainly used as an insecticide against Lepidoptera
Flucythrinate	I	1980s–present	Broad-spectrum insecticide, also used against fruit flies
Lambda-cyhalothrin	I	1980s–present	Mainly against Lepidoptera and Homoptera
Tau-fluvalinate	I/A	1980s–present	Broad-spectrum
Microbial insecticides			It replaced fluvalinate. Mainly used against lepidopterous and aphid pests
			Materials that produce disease in the insect host; very specific, thus mammalian toxicity is low
<i>Bacillus thuringiensis</i> (Bt) subsp. <i>kurstaki</i>	I	1980s–present	Bacteria that produce an exotoxin, which, when ingested, causes gut paralysis. Specific to lepidopterous larvae. Primarily for leaf-rollers
Codling moth granulovirus (CpGV)	I	1980s–present	Viral disease specific to codling moth; used primarily in Europe as a 'soft' insecticide supplement to codling-moth control. Low persistence
<i>Adoxophyes orana</i> granulovirus (AoGV)	I	1990s–present	Viral disease specific to summer fruit tortrix larvae. More effective against first-instar larvae
<i>Beauveria bassiana</i>	I	1980s–present	Fungal disease; dependent on weather conditions; little commercial use as yet
Macrocyclic lactones			A relatively new group of compounds whose active ingredient is from toxins produced by soil microorganisms, large complex molecules, some are semi-synthetic
Abamectin	I/A	1980s–present	Derived from <i>Streptomyces avermitilis</i> ; controls mites, leaf-miners, some areas report control of leafhopper
Spinosad	I	1990s–present	Derived from <i>Saccharopolyspora spinosa</i> ; leaf-roller and leaf-miner control, also thrips and possibly some tephritid fruit flies
Milbemectin	I/A		Derived from <i>Streptomyces hygroscopicus</i> . Activity spectrum similar to that of abamectin; not yet registered in USA/Europe
Polynactins	A		Derived from <i>Streptomyces aureus</i> . Control of spider mites

Continued

Table 19.1. *Continued.*

Class/pesticide ^a	Type (I = insecticide, A = acaricide)	Use period (approximate)	Comments
Insect growth regulators			A newer group of insecticides attacking various points in the insect's hormonal system, thus making them specific to invertebrates and largely non-toxic to mammals. Targets are mostly Lepidoptera, some Homoptera
Benzoylureas (diflubenzuron, hexaflumuron, flufenoxuron, triflumuron, lufenuron, teflubenzuron)	I/A	1970s–present	These compounds act as chitin-synthesis inhibitors. Used mainly against leaf- and fruit-eating lepidopterous larvae (codling moth, leaf-rollers and leaf-miners); some have some effect against rust mites (lufenuron) or spider mites (flufenoxuron); resistance to diflubenzuron has been reported in Europe; never registered in the USA
Fenoxycarb	I	1980s–present	Although chemically a carbamate, it acts as a juvenile hormone analogue, with a strong juvenile hormone-like activity, inhibiting metamorphosis to the adult stage and interfering with the moulting of early-instar larvae; widely used in Europe from the 1980s against codling moth and leaf-rollers; never registered in the USA
Tebufenozide	I	1990s–present	Ecdysone agonist, ^b which acts by binding to the ecdysone receptor protein. As a consequence, the moulting process is lethally accelerated. Used in Europe for the control of codling moth and leaf-rollers
Methoxyfenozide	I	1990s–present	Ecdysone agonist; more active than tebufenozide; codling moth, leaf-rollers, leaf-miners
Pyriproxyfen	I	2000–present	Juvenile hormone analogue, good scale and other Homoptera activity, some suppression of Lepidoptera
Nicotinoids			Neurotoxins that act at the nicotinic site; a newer group of insecticides, fairly broad activity spectrum
Imidacloprid	I	1980s–present	The earliest registration of the group; widely used for aphid control; also effective against other Homoptera, including leafhoppers and mealybugs. Also toxic to apple maggot
Thiamethoxam	I	2001–present	Recently registered; activity spectrum includes Lepidoptera and Hemiptera/Homoptera
Chlorinated sulphur acaricides			
Aramite	A	1950s	A chlorinated sulphite
Chlorfenson (Ovex)	A	1950s	A chlorinated sulphonate, somewhat phytotoxic
Genite 923, Mitox, Fenson	A	1950s–1960s	Closely related chlorinated sulphur compounds
Sulphenone	A	1950s	A chlorinated sulphone. Phytotoxic
Tetradifon	A	1960s–present	Long residual effect, translaminar activity. Also ovicidal

Miscellaneous synthetic organic pesticides

Oxythioquinox	I/A	1960s–present	A heterocyclic carbonate, used primarily as an acaricide, but with some activity against psylla and mildew
Indoxacarb	I	2001–present	A carbamate-like compound, primarily used against Lepidoptera
Pyridaben	A/I	1990s–present	Used mainly in apple orchards as an acaricide against European red mite. It is an inhibitor of the electron transport at mitochondrial level (METI ^c). High knock-down effect and long residual activity to all mobile stages. Toxic to phytoseiids. Risk of developing resistance
Tebufenpyrad	A	1990s–present	Another METI acaricide, but with some activity against summer eggs and also a translaminar action. Toxic to phytoseiids. Risk of developing resistance
Fenazaquin	A	1990s–present	Another METI acaricide with some activity against summer eggs. Toxic to phytoseiids. Risk of developing resistance
Fenpyroximate	A	1990s–present	Acaricide active against Tetranychidae and some effect against Eriophyidae. It acts as a growth regulator. Moderately toxic to phytoseiids
Chlordimeform	A	1970s	A chlornated phenamidine
Propargite	A	1970s–present	A relatively selective acaricide, withdrawn from the US market in the 1990s due to worker dermatitis problems. Still in use in Europe
Hexythiazox	A	1990s–present	It has ovicidal, larvicidal and nymphicidal activity, and also sterilizes females, highly selective, but potential for resistance found soon after introduction. It inhibits the synthesis of chitin
Clofentezine	A	1980s–present	Primarily ovicidal (it inhibits the development of the embryo) and some action against newly hatched larvae, long persistent and highly selective, but potential for resistance found soon after introduction
Amitraz	A/I	1970s–present	Mainly used as an acaricide, to control all stages of tetranychid and eriophyid mites
Other			Materials of this type, some of which have been used for over a century, are enjoying a resurgence of interest, due to their low environmental and human health impact
Oil (petroleum)	I/A	1880s–present	Highly refined narrow-cut petroleum products with emulsifiers added; broad activity against soft-bodied insects and some repellent activity (especially oviposition). Often used as an adjuvant
Oil (plant-derived)		Early 1900s	Mainly used as stickers for other pesticides
Oil (animal-derived)		Early 1900s–present	Primarily fish-oil. Widely used against codling moth in the early part of the century, used in organic production today to some extent
Kaolin clay	I/A	Late 1990s–present	Also known as particle film technology (PFT), this recently introduced compound has a broad spectrum of activity. Probably repellent, or masks plant host
Diatomaceous earth	I	1950s–present	An abrasive silica-containing material mined from deposits of skeletons of marine microorganisms; many industrial uses; little used in apple production

Continued

Table 19.1. *Continued.*

Class/pesticide ^a	Type (I = insecticide, A = acaricide)	Use period (approximate)	Comments
Soap	I/A	1950s–present	Fatty acid derivatives that are broadly toxic to soft-bodied insects; not widely used because of short residual, high cost and potential phytotoxicity. Phosphate-based laundry soaps are also insecticidal
Mating disruption	I	1990s–present	Synthetic chemicals mimicking natural insect pheromones. Not direct toxicants, but reduce insect populations; registered as 'pesticides'. Available for codling moth, oriental fruit moth and some leaf-rollers
Mass trapping	I	1990s–present	Use of pheromones (or other attractants) to catch a high percentage of the adult population. Available for some wood-borers and tephritid flies
Attract and kill	I	1990s–present	Use of pheromones (or other attractants) to attract adults to a droplet of sticky material that contains a rapid knock-down insecticide. Available for codling moth

^aPrimary reference material from western USA and Europe. Key references include Tomlin (2000), ACTA (2001), De Liñán (2001), selected chapters in Fisher and Upshall, (1976). See References

^bAlso known as a moult-accelerating compound (MAC).

^cMETI, mitochondrial electron transport inhibitor

19.2.2 Integrated pest management

The problems with the so-called 'pesticide treadmill' were part of the impetus to re-examine and reorganize pest-management efforts. The use of pesticides engendered a pest-by-pest approach, with little regard for the effect of the sprays on the rest of the agroecosystem (let alone the environment or consumer). With the realization that these dis-junctive efforts were in some cases working against each other, a framework of thought was developed to try simultaneously to account for multiple effects and to solve multiple problems. This theoretical framework became known as 'integrated pest management', or IPM (Stern *et al.*, 1959). Although there are a number of variants (Steiner *et al.*, 1977), this is still the predominant philosophy governing apple pest research.

The guiding philosophy behind IPM was the optimization and harmonization of tactics to achieve 'the best economic, environmental, and social' outcome (Rabb, 1972). While this seems straightforward enough, turning this philosophy into practice has been an ongoing and occasionally hotly disputed process. One overriding difficulty has been evaluating the relative value of a practice where there are clear economic consequences (usually for the producer) and more nebulous, but potentially far-reaching, consequences for society at large. Where the quality and quantity of food production overall are an overriding issue, the value of less expensive or more abundant food has often outweighed the more long-term environmental and social issues. However, in affluent countries with ample food supply and relative economic wealth, the conflict becomes more acute. This is generally reflected in the increasing interest in IPM, integrated fruit production (IFP) and organic production in Europe, the Americas and parts of Asia.

A number of key concepts of IPM form the foundation of most apple pest-management programmes (Metcalf and Luckmann, 1975). The first fundamental concept is to develop some quantitative relationship between the pest population and the loss in yield or productivity. This loss must then be assigned an economic value, based on the projected yield

from the orchard and the value of the crop. The second is that of sampling pest populations in order to arrive at some numerical or risk-based assessment of the population. With these elements in place, a comparison is made between the cost of some control measure and the projected value of crop loss from insect damage. The point at which the two are equal is called the economic injury level (EIL) (Stern *et al.*, 1959). As a general principle, the producer wants to ensure that the insect population does not exceed the EIL (because preventable economic loss occurs), nor is there any particular benefit in merely breaking even. Ideally, the producer needs to forecast the future insect population from the current one (based on previous experience or population growth models) and, when it is clear that the EIL will be exceeded at some future date, the control measure is the preferred course of action.

Not surprisingly, all elements of this system are fraught with uncertainty. Unless the producer is growing his/her fruit under contract, the future value of the fruit is unknown. Indeed, for decisions made early in the season, even the size of the crop is uncertain. Insect population growth is influenced by many factors, including the action of natural enemies, the influence of weather conditions, sprays aimed at other pests or diseases and the tree vigour. All of these modify the insect's innate ability to reproduce (the intrinsic rate of increase (Birch, 1948)), which is the interaction of the number of progeny per female, the time to first reproduction and the sex ratio. Examples of accurate models that are actually in use in apple production are few, if any; however, there is usually a good sense of the potential growth factor of an insect population from one generation to the next in the absence of control measures. In several cases (e.g. tetranychid mites and gracillariid leaf-miners), the modifying effect of natural enemies is partially quantified, such that, at a given predator:pest ratio (Croft, 1975; Avilla *et al.*, 1993) or percentage parasitism (Beers *et al.*, 1993), a reasonable estimate of whether the population will require treatment can be made.

Another aspect to sampling insect populations is monitoring their phenological development in order to determine the opti-

mum timing for control measures. Insects are poikilotherms and speed or slow their development in response to ambient temperature. This principle underlies the concept of physiological time, using some type of time-temperature summation (e.g. degree-days). Computer simulations of development (degree-day models) were developed for many pest species (e.g. codling moth (Fig. 19.2)). This degree-day model has been applied most often to the determination of optimum timing of pesticide applications, but is equally applicable to (for example) distributing mating-disruption dispensers in the orchard or releasing a biocontrol agent. Since monitoring some species may be difficult (due to extremely low population levels) or time-consuming, phenological models have been developed to facilitate the process. These models, often driven by fairly simple temperature inputs (daily maxima and minima) and some initialization point (often the first capture of an adult in a pheromone or visual/odour trap), provide producers with greatly improved accuracy of determining insect-stage development. They do not, however, tell the producer anything about the need for control measures, which must be accomplished by other means.

19.2.2.1 IPM tactics

In one sense, almost any pest-control tactic may potentially have a place in an IPM framework. Some tactics tend to be more often associated with IPM or viewed more favourably. It should be noted at the outset that the use of insecticides and acaricides, in the appropriate circumstances, is considered a legitimate IPM tactic. Increasingly, IPM is defining the characteristics of appropriate pesticides more and more narrowly. In any case, pesticide use must always be context-sensitive: the insect must have reached some critical population level to warrant treatment; the optimum timing and placement of the material must have been considered; the most appropriate compound must be chosen in light of its effects on natural enemies and other pests in the orchard. In addition, factors such as worker and environmental safety are being given more weight in the decision-making process.

Biological control is considered in many ways to be the ideal pest-management tactic, because it tends to be environmentally innocuous, self-sustaining and low cost. Each of these characteristics may depend a great deal on the system in question. The low environmental impact of biological

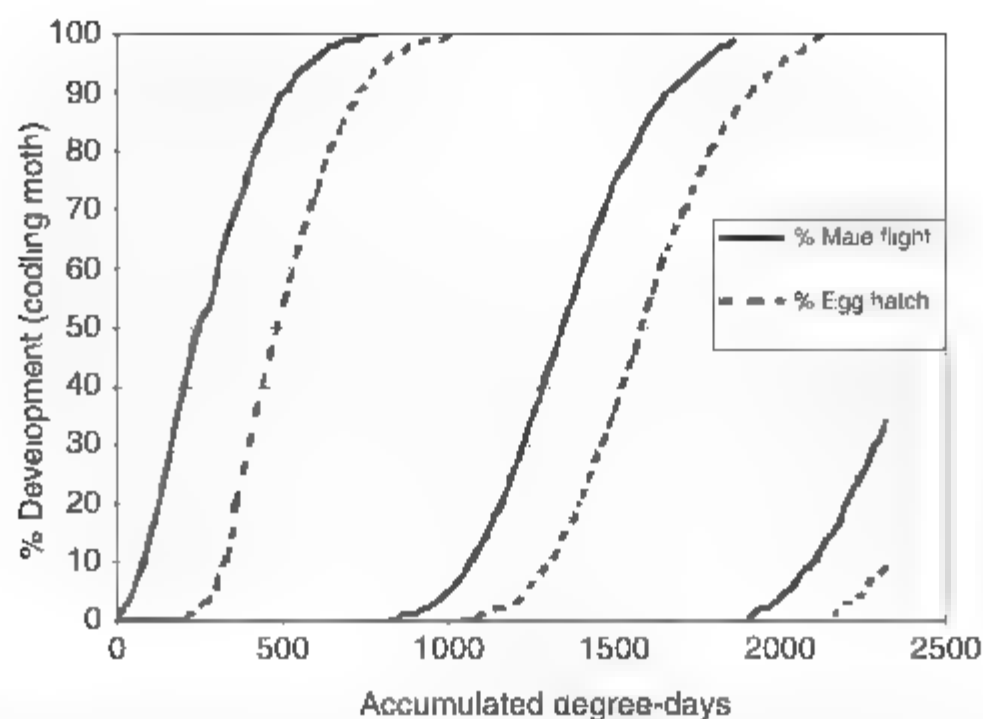


Fig. 19.2. Codling-moth degree-day model. Degrees are calculated using a horizontal cut-off sine-wave method, with lower and upper temperatures of 10 and 31°C, respectively (Brunner *et al.*, 1982)

control was formerly considered dogma, recent studies (Follett and Duan, 2000), however, point out that ecosystem disruption from imported organisms can be extensive and unexpected.

Conservation biological control is arguably the easiest and thus most frequently pursued. This approach uses a natural enemy species that already occurs in the region and makes the environment more favourable for its growth and development. This can include cultivating plants in the vicinity of the orchard that provide an alternative insect host or habitat or avoiding pesticides that are toxic to one or more life stages. The latter is often referred to as 'integrated control' or the integration of biological and chemical control tactics. Classical biological control is the importation of a natural enemy, often from the region where the crop originates, which has the capacity to provide complete economic control of the pest in question. The purest form of this type is in minimally managed systems, where pesticide use for other pests does not disrupt the imported natural enemy. Examples of this type are rare in tree fruits, because the use of at least some pesticides is ubiquitous. However, there is still an interest in the importation of natural enemies, which, if established, become candidates for conservation biological control. The last methods involve ongoing releases of artificially reared natural enemies; these can occur either occasionally (augmentative) or in the form of a 'biological pesticide' (inundative). Because the expense of rearing natural enemies can be considerable, the latter two methods have been little implemented.

Cultural control involves manipulating the orchard or the immediate environment to reduce pest numbers or mitigate pest damage. Irrigation may reduce water stress and allow arthropod-stressed trees to produce better than they could otherwise. Orchard-floor management (e.g. the mix of plants in the row middles) may allow more natural enemies to build up in the cover crop and be available to reduce arboreal pest populations. Reducing fertilization so that vegetative growth is minimized may slow the population growth of flush-feeding insects,

such as aphids. Cultivars or strains that have reduced terminal growth, such as the spur-type cultivars, may play the same role. In general, however, producers prioritize plant growth and productivity in their orchard-management practices, which may conflict with the optimal pest-control practice.

Host-plant resistance, while frequently used in field crops, has played a very small role in arthropod-pest management of orchard crops. The horticultural characteristics, especially precocity, productivity, flavour and storability, are the primary drivers of cultivar choice. One notable exception is the use of resistant rootstocks for woolly apple aphid.

Ultimately, IPM can be viewed as just another evolutionary step in our overall problem-solving process in agriculture. More recently, theories have emerged (primarily in Europe and New Zealand) that take the next logical step of integration to the entire production system – integrated fruit production, or IFP (Boller *et al.*, 1998; see Chapter 21). To an extent, this may be viewed as a reincarnation of the organic-production philosophy (see Chapter 22), which also encompasses all aspects of the production system but with the additional caveat of restricting the materials used to only naturally occurring, minimally processed products (in terms of pesticides, plant-growth regulators and fertilizers)

19.3 Fruit Feeders

This group of insects attacks the fruit directly, leaving either feeding scars or deep entries, potentially serving as an infection site for pathogens. The EILs for these pests are relatively straightforward for fresh-market fruit, because virtually all defects are removed during packing. The issue is somewhat clouded for processing fruit, where some level of damage, especially healed surface damage, does not detract from the utility or quality of the fruit. Overall, pest-management programmes have focused most intensely on this group of pests because of their clear and apparent effect on usable yield.

The fruit may be attacked at almost any point during the growing season, from early in the bud stage to harvest. Fruit attacked early in the season is more likely to abscise naturally, or it can be selectively thinned during hand-thinning. Fruit attacked during the mid-season is more likely to stay on the tree and thus has a higher likelihood of being harvested. Fruit attacked very late may generate sufficient ethylene to abscise prematurely and has a slightly reduced chance of entering the packing or processing plant. Clearly, excessive amounts of fruit drop just before harvest will have a detrimental effect on yield.

19.3.1 Direct pests of buds and fruitlets

19.3.1.1 Noctuids (*Lepidoptera: Noctuidae*)

There is a complex of species in this family in which the young larvae feed on developing buds and fruitlets. The feeding damage can prevent development, cause premature abscission or leave deep scars that distort the fruit. This group, called the green fruitworms in North America, include *Orthosia hibisci* (Guenée), *Amphipyra pyramoides* (Guenée) and *Lithophane antennata* (Walker). Several species, such as *Orthosia incerta* (Hufnagel), may be found in Europe, depending on the region (Carter, 1984). These pests may be regionally important, but are generally considered minor. Pheromones may be used to monitor their flight to help predict phenology and relative abundance, e.g. *Graphania mutans* in New Zealand (Burnip *et al.*, 1995).

19.3.1.2 Weevils (*Coleoptera: Curculionidae, Attelabidae*)

Although several different species of weevils are known to feed on buds, fruit, foliage and woody tissue of apple trees, only two are considered to be major pests against which apple growers take specific action. These are the apple blossom weevil, *Anthonomus pomorum* (L.), a native and widespread pest of apples (and occasionally pears) in Europe (Toepfer *et al.*, 1999), and the plum curculio,

C. nenuphar (Herbst), which has become a key pest of apple and other pome and stone fruit in its native range of eastern and mid-western North America. In addition, several species of *Rynchites* are local or sporadic pests in Europe.

Apple-blossom weevil adults feed on developing apple buds in spring. Feeding is followed by oviposition and larval feeding on the bases of flower petals, resulting in sterility and a brown-capped appearance of the flowers. Low to moderate populations may act as natural blossom thinners. Large populations, more common in recent years, can overthin the crop. Plum-curculio adults likewise feed on developing apple buds in spring but also feed upon and then oviposit into young fruitlets, where larvae tunnel and cause most injured fruitlets to drop. Injured fruit remaining on trees are scarred by the feeding and ovipositional wounds, which usually render injured fruit unmarketable. Whereas apple-blossom weevils and northern populations of plum curculios have one generation per year, more southern populations of plum curculio have an additional generation and threaten not only fruitlets but also apples approaching maturity.

An understanding of the ecology of these weevil species is the key to successful management (Vincent *et al.*, 1999). Both species can build into large populations on unmanaged host trees. In some locales, plum curculio annually infests 90% of the fruit on unmanaged trees. Although resident vertebrate and invertebrate predators, parasitoids and pathogens do have some impact, the degree of population suppression by these biocontrol agents has generally been insufficient to maintain infestations below levels that threaten the quality of buds or fruitlets. Fortunately, adults of both species have rather limited flight capability, usually no more than a few hundred metres. Even so, many blocks of apple trees in Europe and eastern and midwestern North America have at least one border exposed to sufficient numbers of nearby unmanaged hosts to constitute high susceptibility to invasion. Another important ecological consideration is overwintering, which occurs in the adult stage, when individuals move in autumn

from infested trees to protected sites beneath fallen leaves, bark or debris at margins of nearby woods or hedgerows. Finally, when overwintered adults migrate into orchards in spring, there is a strong propensity for establishment on perimeter trees and successively less propensity for movement on to interior trees with increasing distance from the perimeter.

Application of organophosphate or other insecticides timed to coincide with pulses of adult immigration continues to be the main approach to managing both of these pests. Because there still exists no truly effective trap for monitoring immigrant adults (Prokopy *et al.*, 1999), timing of application is based on degree-day models that predict periods of immigration (Reissig *et al.*, 1998). Improved understanding of the ecology of these species has facilitated excellent orchard-wide control using a much-reduced amount of material through restricting application to only those orchard trees most likely to become infested, i.e. trees within 20 m or less of the perimeter (Vincent *et al.*, 1997).

19.3.1.3 Mirids (Hemiptera: Miridae)

Like the weevils, the serious mirid pests of apple are orchard invaders, completing the majority of their life cycle outside the orchard and immigrating only during brief periods to feed on fruit. This presents an additional challenge to pest management in that the grower is forced to respond reactively, rather than being able to take proactive steps in management. The tarnished plant bug or *Lygus* bug (*Lygus lineolaris* Palisot de Beauvois) (Plate 19.1) is a sporadic pest of apple. It pierces the developing fruitlet with its piercing-sucking mouth-parts, leaving a deep, inverted dimple on the mature fruit. Although the mullein plant bug (*Campylomma verbasci* (Meyer)) feeds in a similar way, it leaves a raised corky wart on the fruit. Several other pests in the same group occur in different areas of Europe and North America, including the genera *Lygocoris*, *Lygidea*, *Heterocordylus* (Boivin and Stewart, 1982), *Campyloneura*, *Plesiocoris*, *Blepharidopterus* (Alford, 1984) and *Atractotomus* (MacPhee,

1976). With the exception of *L. lineolaris*, most of the apple-feeding mirids are facultatively predacious and thus are considered natural enemies as well as pests.

19.3.1.4 Thrips (Thysanoptera: Thripidae)

Thrips are serious and widespread crop pests worldwide, but have few representatives in the apple pest complex. The most common species is *F. occidentalis* (Pergande). The adults are attracted to blooming plants and are often present in the orchard on blooming weeds. When apple blossoms open, they move to developing fruits. Their feeding activities (sucking mouth-parts) cause a condition called 'pansy spot' on sensitive cultivars, and they leave a small oviposition scar in the centre of the pansy. The damage is most apparent on light-coloured cultivars, often colouring over on deeply coloured sports (Plate 19.2). The pear thrips, *Taeniothrips inconsequens* (Uzel) is primarily a pest of pear and sugar-maple, but is an occasional pest of apple.

19.3.1.5 Sawflies (Hymenoptera: Tenthredinidae)

Hymenopterous pests of apple are few in number (see also late-season direct fruit feeders). *Hoplocampa testudinea* (Klug), the apple sawfly, is a widespread and sometimes serious pest of apple in Europe (Giraud *et al.*, 1996), although elevated natural mortalities may be caused by various fungi and the ichneumonid *Lathrolestes marginatus* (Jaworska, 1992). The adults appear during bloom and lay eggs in the flower, giving rise to larvae that burrow and feed in the fruit. The adults may be monitored with white sticky panels.

19.3.2 Mature-fruit feeders

19.3.2.1 Codling moth

BIOLOGY Codling moth, *C. pomonella* (L.), is the main direct pest of apples worldwide and has been extensively studied (e.g. <http://ippc.orst.edu/codlingmoth>) (Plate 19.3). It is not reported as present in Japan,

Taiwan, Korea or eastern China, but is otherwise cosmopolitan. It is present in the urban areas of the Brazilian apple-growing area, but it has not yet invaded the orchards. There are typically between one and four generations per year, depending on the climate. The level of infestation on untreated apple trees can reach 100% of fruit infested, with evidence of multiple 'stings' or larval attacks. The economic threshold for codling moth is low (c. 1% damaged fruit), even for crops that are not exported. These factors have combined to make this pest one of the greatest scourges for apple growers. It is also one of the most researched and consequently best understood insect pests. The absence of the insect from Asian growing regions has led to stringent procedures, including fumigation of apples and other potential host fruit with methyl bromide (e.g. Maindonald *et al.*, 1992).

Female moths oviposit single eggs on or near developing fruit. Larvae hatch out and locate apples on the basis of an apple fruit volatile, (*E,E*)- α -farnesene (Sutherland and Hutchins, 1972). Larvae then begin to enter the fruit and make their way to the core to feed on the seeds, like other members of the genus *Cydia* (Witzgall *et al.*, 1996b). The entrance hole is frequently plugged with frass. Mature larvae emerge from the fruit with a characteristic exit hole. Diapausing fifth-instar larvae overwinter in cocoons in suitably protected locations under the bark of the host tree or on the ground. Factors contributing to population regulation of codling moth have been the subject of considerable research. There appears to be general acceptance of the findings of Geier (1963) that limited supply of fruit and overwintering sites are the key factors limiting codling-moth populations on unmanaged trees.

The main recorded hosts are apple, European pear, nashi (Asian pear), Chinese pear and quince. Walnut and plum are consistently attacked, while peach, nectarine and apricot are also recorded hosts, and damage can be significant in some situations. Differences in the host preference, development, diapause, phenology and population dynamics have been found for strains or races of the moth taken from apple, plum or

walnut host plants (Barnes, 1991). The removal of alternative or abandoned host trees can therefore make an important contribution to control by reducing migration of the pest into smaller orchards.

DETECTION AND INSPECTION METHODS Pheromone traps have been used for detecting adult male codling moths since the initial pheromone identification (Roelofs *et al.*, 1971). This is one of the best understood and most widely used pheromone monitoring systems. A number of different management approaches have been based on pheromone-trap detection of males, including forecasting female moth flight and oviposition from sustained male flight activity, used with day-degree accumulation (Riedl, 1976), spray thresholds based on the number of moths in standard traps (Wearing and Charles, 1978) and the use of traps to determine the efficacy of mating disruption, sometimes with lures with higher pheromone loads to overcome the pheromone background (Charmillot, 1990).

Cardboard bands applied at the right time around tree trunks to collect diapausing larvae are useful for estimating the number of larvae per tree (Eyer, 1937) and have been widely used in research and by organic growers for cultural control. They may be especially useful for comparing the larval populations from year to year in a given orchard. Direct observation of damaged apples during the growing season is another obvious method of monitoring the pest population, although detection of a direct pest at harvest is usually too late for economic production where there is a single generation.

CHEMICAL CONTROL For much of the 20th century, chemical control was the most widespread method of pest control. However, after usage and selection for populations with genetic resistance to arsenic (Hough, 1928), followed by the same pattern with dichlorodiphenyltrichloroethene (DDT) (Glass and Fiori, 1955), orchardists have switched to other broad-spectrum insecticides. Development of resistance to other insecticides has occurred, although it has not always occurred in all countries or been documented adequately.

Organophosphates were the next chemical group used in many countries (azinphos-methyl, phosmet, diazinon and phosalone), but resistance is now widely recorded (Barnes and Moffitt, 1963; Bush *et al.*, 1993; Varela *et al.*, 1993; Blomefield, 1994; Knight *et al.*, 1994). Pyrethroids (bifenthrin, cyfluthrin, cypermethrin, deltamethrin, esfenvalerate, fenpropathrin, fenvalerate, flucythrinate, fluvalinate and permethrin) have seen some acceptance in the eastern USA (primarily for leaf-roller control), although the trend in much of Europe has been to avoid such broad-spectrum insecticides due to their negative impacts on natural enemies.

In Europe, more selective insecticides have been increasingly used, including juvenoids (such as fenoxycarb (Charmillot, 1989)), chitin synthesis inhibitors (diflubenzuron, triflumuron, chlorfluazuron and teflubenzuron) and ecdysone agonists (e.g. tebufenozide and methoxyfenozide) (Heller *et al.*, 1992). However, there are also examples of resistance to these compounds (Moffitt *et al.*, 1988; Sauphanor and Bouvier, 1995). In addition, avermectin (a macrocyclic lactone fermentation product) has some efficacy (Cox *et al.*, 1995), as does spinosad, another fermentation product. The advantage of more selective insecticides is the reduced impacts on natural enemies, permitting the maximum contribution of biological control against other pests. Petroleum oils have been used as ovicides (Webster and Carlson, 1942), although earlier products often caused phytotoxicity. More recently, highly refined and purified products have been shown to have good efficacy (Riedl *et al.*, 1995) and have reduced phytotoxicity problems. Particle films (Unruh *et al.*, 2000) also have some efficacy against codling moth.

Mechanical control, using bands on tree trunks to collect diapausing larvae, has also been used, but these do not collect the proportion of the population that falls to the ground directly. They can be effective if used in conjunction with other tactics (e.g. Judd *et al.*, 1997)

BIOLOGICAL CONTROL There are a range of biological control agents of codling moth,

attacking by predation (Knight *et al.*, 1997) or parasitism (Hassan, 1989) of eggs and neonate larvae (MacLellan, 1972). The cryptic habit of the larval stages (including diapause) offers some protection against natural enemies. In some situations, bird predation of diapausing larvae can be significant (Wearing and McCarthy, 1992). However, the high levels of damage typically observed in the absence of controls indicate that biological control, if present, is insufficient to maintain the pest below the economic threshold, which is relatively low

MATING DISRUPTION The release of sufficient synthetic sex pheromone to delay or prevent mating and provide control of codling moth has been researched extensively worldwide, based on promising results with a range of formulations (Charmillot, 1978; Moffitt and Westgard, 1984; Gut *et al.*, 1992; Minks and van Deventer, 1992; Judd *et al.*, 1997). The mechanisms by which disruption acts are not entirely clear (Minks and Cardé, 1988) and it may be possible to use pheromone-related compounds to improve results (Witzgall *et al.*, 1996a).

Mating disruption is inversely density-dependent and therefore works best at low pest densities in sites without significant immigration. It is not as effective in situations where the pheromone cloud is difficult to maintain (steep slopes, windy sites, missing trees or uneven orchard canopy) or in close proximity to unmanaged populations. The first commercially available pheromone dispenser for control of codling moth (Isomate-C®) became available in the USA in 1991. Mating disruption of codling moth is now commercially accepted in several countries, and c. 40,000 ha of orchards were treated with pheromone formulations in Washington, California and Oregon in 2000 (G. Thayer, Oregon, 2000, personal communication). This has occurred in part because of the failure of conventional insecticides, due to resistance, as well as the intrinsic environmental and worker safety of pheromone products

Although codling-moth mating disruption is not yet registered in all European countries, it has been widely used in some

areas (e.g. northern Italy). The relatively higher cost of this technique slows its adoption, especially in warmer regions where two applications per season of the dispenser are necessary.

MASS TRAPPING AND ATTRACTICIDAL CONTROL Mass trapping has not proved to be very effective against codling moth (e.g. Proverbs *et al.*, 1975), in part because of the cost and practical difficulties of deploying sufficient stations. As with mating disruption, the tactic aims to prevent mating and therefore pest progeny. However, whereas in mating disruption males can survive to find a mate the next night, this is not possible where males have been removed from the system, which represents a potential strength of the approach. If droplets containing sex pheromone and a fast-acting insecticide are used instead of traps (Charmillot *et al.*, 1996), then the costs can be somewhat reduced. It may also be possible to develop multiple-species attracticides (Suckling and Brockerhoff, 1999).

STERILE-INSECT TECHNIQUE Although it is technically feasible (e.g. Proverbs *et al.*, 1982), sterile-insect release is expensive and has several important limitations. Most importantly, it requires mass rearing with specialized capital-intensive facilities, excellent quality control to maintain mating competitiveness with feral insects, geographical isolation, political support and ongoing investment in the event of movement of contaminated fruit. There are apparently few regional orchard industries that meet these criteria. A sterile-insect release programme was commenced in the 1990s to eradicate the codling moth from the 8000 ha of apple and pear trees in the Okanagan valley in British Columbia. While successful in some respects, the goal of eradication has not been realized and the programme has been redirected to a minimal-insecticide control programme (H. Thistlewood, personal communication).

MICROBIAL CONTROL The most promising microbial control against codling-moth neonate larvae is a granulosis virus (Tanada, 1964), which has been tested extensively in

Europe (Audemard *et al.*, 1992), including the UK (Glen and Payne, 1984), New Zealand (Wearing, 1990) and the USA (Westigard and Hoyt, 1990). In hot climates with high levels of solar radiation, the persistence of the virus in the field is poor (about 1 week), making frequent applications necessary. However, its effectiveness against high pest populations, in combination with mating disruption, offers organic apple growers an effective way of reducing pest populations to levels at which mating disruption can operate effectively. Commercial use of the virus has unfortunately been limited by the costs of production using live insects. Industrial-scale production offers reduced costs to growers (M. Guillon, personal communication), which should assist adoption in future.

19.3.2.2 *Oriental fruit moth and other Grapholita (= Cydia) species*

Grapholita molesta (Busck) (Plate 19.4) and other members of the *Grapholita* genus, such as *G. lobarzewski* (= *Cydia lobarzewski*) and *G. janthinana* (*Cydia janthinana* (Dup.)) are sometimes recorded as pests of apple (Kalman *et al.*, 1994). In several countries, *G. molesta* (or oriental fruit moth) is reported to be increasingly important as a pest of apples (e.g. Reis *et al.*, 1988; Pollini and Bariselli, 1993). These species typically feed on shoots early in the season, as well as fruits later in the season. The biology and options for control are similar to those for codling moth, but the pest status may not always warrant intervention. Within the past few years, oriental fruit moth has emerged as a major pest in several mid-western and eastern US growing districts, surpassing codling moth in importance.

19.3.2.3 *Tephritid fruit flies (Diptera: Tephritidae)*

True fruit flies of the family Tephritidae (Aluja and Norrbom, 2000) deposit eggs directly into the flesh of developing fruit, particularly fruit approaching readiness for harvest. The tiny puncture made through the skin of fruit during egg-laying is difficult to detect without magnification and may remain so even when underlying flesh has decayed substantially.

during larval feeding. Commonly, infested fruit are detected only after a few days of exposure to room temperature following purchase by an unwary consumer

Three species of tephritid flies are key pests of apples in geographical areas where their presence coincides with commercial apple production. The apple maggot fly, *R. pomonella* (Walsh) (Plate 19.5), is native to North America and is not known to occur elsewhere. It is especially important as a pest of apples in eastern and midwestern regions. It has a more limited, but growing, distribution in the western fruit-growing regions. The Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), is native to Africa and has spread to most fruit-growing regions of the world. It has become an important pest of apples in Middle Eastern countries, including Israel, Syria and Turkey. The South American fruit fly, *Anastrepha fraterculus* (Wiedemann), is native to South America but has spread to Central America and Mexico. Recently, it has begun to damage commercially produced apples in southern Brazil (Sugayama *et al.*, 1998). For all three species, there is an extremely low tolerance, bordering on zero, for larval-infested fruit, especially fruit intended for export.

Sometime during the past two centuries, all three species expanded their host range to include apples. In the process, they have escaped most of their natural enemies (particularly parasitoids), which provide some biological control of fruit-fly eggs or larvae in native host fruit. Apparently the chemical and physical properties of apples are sufficiently similar to those of the native hosts of these flies to have facilitated fly colonization of apples but are different enough from the native hosts to exclude colonization by parasitoids, most of which respond only to highly specialized cues when searching for hosts. In consequence, fly populations on feral or otherwise unmanaged apples or other newly acquired host trees can build to large numbers and severely threaten apple orchards within a kilometre (in the case of apple maggot fly) or more (in the case of Mediterranean and South American fruit flies). Despite grower vigilance in preventing fly oviposition and larval development in commercial

orchards, annual invasion by adults from beyond orchard perimeters represents a major challenge to managing these pests. In many situations, not owning the land beyond orchard perimeters severely compromises growers' ability to reduce invading flies through eliminating nearby unmanaged host trees. This may be especially problematic where orchard blocks are comparatively small and perimeters are exposed to considerable non-orchard vegetation.

Currently, all three pest species are managed primarily by applications of organophosphate insecticides, although in some areas the preharvest interval dictates the use of pyrethroids. Applications are timed in accordance with the occurrence and abundance of captures of invading adults by monitoring traps placed on perimeter trees. Predictive phenology models (Jones *et al.*, 1989) have been useful in determining the timing of emergence. In some cases, confining insecticide application only to perimeter trees or baiting perimeter trees with odour-visual traps has provided effective control (Cohen and Yuval, 2000; Prokopy *et al.*, 2000). Even though there are no known cases of insecticide resistance in any tephritid fly, the need for continuous protection of apples by insecticide residue over the course of the 2–3-month period of susceptibility to fly oviposition is prompting some growers to seek alternative approaches to fly management.

19.3.2.4 Leaf-rollers (Lepidoptera: Tortricidae)

BIOLOGY Leaf-rollers have only an indirect physiological impact on the tree, since they feed on the fruit surface rather than the seeds. While the impact on the tree may be negligible, the impact of fruit feeding on grower returns is a direct one. Leaf-rollers emerge as a major concern in many orchards that apply selective controls for codling moth, as well as for exporters forced to meet quarantine tolerances with a nil threshold. Larvae typically web foliage together and many also feed directly on the fruit surface. This cryptic habit has often made insecticidal control difficult. Fruit damage is visible as scarring or corking or as rots associated with open wounds in storage, and larvae occa-

sionally enter the apple calyx. Injury to fruits destined for fresh and especially export markets has the most significant economic impact, compared with that of processing-grade apples.

Leaf-roller biology differs in several important ways from the internal feeding tortricid species (van der Geest and Evenhuis, 1991). Many have much wider host ranges and feed on leaves as well as fruit (Chapman and Lienk, 1971). Their external life habit is accompanied by larval dispersal through ballooning, typically followed by the establishment of a larval nest on shoots or the undersides of leaves. Larger larvae are able to relocate to fresh nests and use their silken thread for both nest construction and escape. Many species are multivoltine, with up to four generations per year. Unlike codling moth, few leaf-roller species are geographically widespread. Instead, apple-growing regions typically have a unique complex of leaf-roller species (Table 19.2; Chambon, 1986).

HOST RANGE Many leaf-rollers attacking apple have very wide host ranges. The following represents a partial list of hosts of the light brown apple moth, *Epiphyas postvittana*, to indicate the range of economically important alternative hosts: *Actinidia chinensis* (kiwifruit), *Chrysanthemum* × *morifolium* (chrysanthemum

(florists')), *Crataegus* (hawthorns), cotoneaster, *Eucalyptus*, *Humulus lupulus* (hop), *Jasminum* (jasmine), *Ligustrum vulgare* (privet), *Litchi chinensis* (lychee), *Macadamia integrifolia* (macadamia nut), *Medicago sativa* (lucerne = alfalfa), *Pinus* (pines), *Prunus persica* (peach), *Prunus armeniaca* (apricot), *Pyrus* (pears), *Quercus* (oaks), *Rubus* (blackberry, raspberry), *Solanum tuberosum* (potato), *Trifolium* (clovers), *Vicia faba* (broad bean), *Vitis vinifera* (grapevine), *Ribes* (currants), *Rosa* (roses), citrus, *Diospyros* (malabar ebony), *Populus* (poplars), *Vaccinium* (blueberries).

DETECTION AND INSPECTION METHODS Pheromones are known for many tortricids affecting apples (<http://www.nysaes.cornell.edu/pheronet>), and traps have been widely used for detection and monitoring of leaf-roller populations. A range of applications were reported by Suckling and Karg (2000), including species-distribution surveys, insecticide-resistance monitoring, insecticide spray-reduction programmes and sample collection for population studies. More labour-intensive systems involving larval assessments on shoot tips have also been used for predicting the size of subsequent generations within a season.

Modern diagnostic methods are also under development for a range of tortricids. Several DNA methods have been used for species

Table 19.2. Abbreviated list of leaf-roller pests affecting apple in various regions.

Species	Common name	Distribution
<i>Adoxophyes orana</i> (Fischer von Röslerstamm)	Summer-fruit tortrix	Europe, Asia
<i>Archips argyrospila</i> (Walker)	Fruit-tree leaf-roller	North America
<i>Archips brevipicanus</i> (Walsingham)	Asiatic leaf-roller	Asia
<i>Archips podana</i> (Scopoli)	Great brown-twist moth	Europe, Asia
<i>Archips rosana</i> (L.)	European leaf-roller	Europe, USA
<i>Archips xylosteanus</i> (L.)	Apple leaf-roller	Eastern Europe
<i>Argyrotaenia velutinana</i> (Walker)	Red-banded leaf-roller	Eastern USA
<i>Choristoneura rosaceana</i> (Harris)	Oblique-banded leaf-roller	North America
<i>Epiphyas postvittana</i> (Walker)	Light brown apple moth	Australia, New Zealand
<i>Pandemis heparana</i> (Denis and Schiffmüller)	<i>Pandemis</i> leaf-roller	Europe
<i>Pandemis limitata</i> (Robinson)	<i>Pandemis</i> leaf-roller	North America
<i>Pandemis pyrusana</i> Kearfott	<i>Pandemis</i> leaf-roller	Western USA
<i>Platynota flavedana</i> Clemens	Variegated leaf-roller	Eastern USA
<i>Platynota idaeusalis</i> (Walker)	Tufted apple-bud moth	Eastern USA

identification (Sin *et al.*, 1995; Gleeson *et al.*, 2000), and this approach should provide ready taxonomic support for ecological studies.

BIOLOGICAL CONTROL Reduction in broad-spectrum insecticide use on apple is typically accompanied by an increase in biological-control activity of leaf-rollers and other pests. An example is the spread of the parasitoid wasp *Colpoclypeus florus* Walker (Plate 19 6) for control of the oblique-banded leaf-roller, *Choristoneura rosaceana* (Harris) (Plate 19 7) after the reduction of organophosphate use in Washington. In many cases, leaf-roller parasitoids and predators are present on alternative host plants outside orchards and follow the pest populations across a range of host plants (Suckling *et al.*, 1998). A fuller treatment of leaf-roller biological control is present in Mills and Carl (1991).

19 3 2 5 Cutworms and fruit worms (Lepidoptera: Noctuidae)

Although minor in importance in comparison with the tortricids, several species are capable of fruit feeding later in the season. The larvae excavate shallow round holes in the fruit, rendering them unmarketable. The spotted cutworm (*Xestia c-nigrum* (L.)), Bertha army worm (*Mamestra configurata* Walker), variegated cutworm (*Periodroma saucia* (Hubner)), black cutworm (*Agrotis ipsilon* Hufnagel) and the western yellow-striped army worm (*Spodoptera praefica*) are a few of the species that can damage apple fruits and leaves. More recently, a new species, *Lacanobia subjuncta* (Grote & Robinson), was recorded from Washington State (Landolt, 1998) and has become an important pest in some areas.

19 3.2 6 Fruit-stinging insects (Hemiptera)

Pests in this group are also orchard invaders and damage levels are often highest around the orchard borders. The surrounding habitat is a primary determinant of the intensity of attack. The most common example are the stinkbugs (Pentatomidae; *Euschistus conspersus* Uhler and *Acrosternum hilare* (Say)), but the western box-elder bug (*Leptocoris rubro-*

lineatus Barber; Hemiptera: Rhopalidae) has similar pest status. Damage usually occurs in the latter part of the season and is characterized by a spongy, depressed area c. 1 cm in size surrounding the feeding puncture. Externally, damage can resemble physiological disorders such as bitter pit, but the tissue beneath the skin does not turn brown.

19.3.2.7 Miscellaneous opportunists

A number of insects are attracted to ripening or overripe fruit and will either create a point of entry or enlarge damage due to other causes (splits, stem punctures, etc.). Vespid wasps are often found in orchards near harvest and, although they are primarily predacious, they chew holes in ripe fruit and pose a hazard to harvesters. Nitidulid beetles are also attracted to ripening fruit and can be found feeding under the surface. Earwigs are orchard residents that are usually predacious, but will also chew or enlarge holes in fruit. They can curl up in the stem cavity and make their way into the packing-house. The dock sawfly, *Ametastegia glabrata* (Fallén), tunnels into the fruit, especially those close to the ground, in order to find an overwintering shelter.

19.4 Foliage Feeders

There are multiple groups of arthropods that attack and feed mainly on foliage, with the primary damage being loss of photosynthetic capacity due to loss of chlorophyll and disrupted osmotic balance. From the perspective of plant productivity, specifically yield parameters, the effect of chlorophyll loss is controversial. No clear and uncontested relationships have been established, although it seems clear from the body of literature that there is not a directly proportional relationship between loss of chlorophyll and loss of photosynthetic capacity.

Trees are capable of sustaining a certain degree of foliar damage without any measurable loss in yield; thus, the critical question becomes: 'How much damage?' The studies performed attempting to establish such relationships quantitatively have been

restricted in interpretation to the particular combination of cultivar, climate and growing regime in which they were conducted and, as a consequence, the results and interpretation have been quite variable.

The implication of some level of tolerable damage has a critical implication for IPM: the latitude for biological control. In many cases, some level of the pest population must survive in order for the natural enemy to survive (unless there is an alternative host). Unlike pests of quarantine importance or direct fruit feeders, there is a greater window of opportunity for non-pesticidal control measures, since the need for control is not so immediate or triggered at a low threshold. Given the societal emphasis on reduction in pesticide use, this characteristic should be more fully exploited in the future.

Many of the foliage feeders are classed as secondary (in importance) or induced pests. The latter classification implies that they would not have achieved pest status without pesticide inputs directed at a primary (often direct) pest. Again, this points to the opportunity to regulate this group using non-pesticidal methods, or only on an occasional basis.

19.4.1 Mesophyll stylet feeders

This group feeds on cellular contents (including chlorophyll) by penetrating the leaf surface (often from the underside), killing only one or a group of cells at each feeding site. The damage appears as speckling (leafhoppers) or bronzing (tetranychid and eriophyid mites), depending on the size of the mouth-parts and the depth of penetration. Reduction in photosynthesis may follow extensive feeding, due possibly to a combination of chlorophyll loss and/or stomatal closure caused by water loss.

19.4.1.1 Tetranychid (spider) mites

Several species are worldwide pests of apple, including the European red mite (*P. ulmi* (Koch) (Plate 19.8) and two-spotted spider mite (*T. urticae* Koch) (Plate 19.9). Other species (*T. mcdanieli*, *Tetranychus vien-*

nensis, *Eotetranychus carpini*, *Bryobia* spp.) cause a similar type of damage, but are regional in distribution. A few species of tenuipalpids (false spider mites) and tarsonemids (e.g. *Cenopalpus pulcher* Canestrini & Fanzago) are apple pests in some regions (Jeppson *et al.*, 1975b).

The biological control of spider mites is well studied and implemented, with varying degrees of success. The predatory mites in the family Phytoseiidae (Kostianinen and Hoyt, 1996) are the most frequent and successful biological-control agents (e.g. *Typhlodromus* (= *Galandromus* = *Metaseiulus*) *occidentalis* (Plate 19.10), *Typhlodromus pyri* Scheuten, *Amblyseius fallacis* (Garman), *Amblyseius andersoni* (Chant), *Neoseiulus californicus* (McGregor)) (Jeppson *et al.*, 1975a). Different species are better adapted to different growing regions; for example, *T. occidentalis* is ideally suited to the arid climate of the western USA, whereas *T. pyri* requires a more humid, temperate climate (Beers *et al.*, 1993). *T. pyri* is the most important mite predator in the temperate regions of Europe (excluding Scandinavia and the Mediterranean region). It is widely used for European red-mite control, often through the release of organophosphate (OP)-resistant strains (Blommers, 1994). The number of years needed to achieve successful spider-mite control may vary between 1 (temperate conditions) and 3 (cooler conditions). *T. pyri* does not occur in the Mediterranean area, where summers are too hot and dry. *A. andersoni* is the most important predator in these areas, where its natural populations can very successfully control the pest populations (García-Marí *et al.*, 1989).

Several predatory mite species have adapted well to orchard spray regimes, and this is, in large part, the reason why integrated control programmes have been possible (Hoyt, 1969). In addition, several species are reared commercially and sold for release in orchards either as an inoculative measure or as a sort of 'living pesticide'; some strains have been selected for tolerance to pesticides (Hoyt and Knop, 1981; Roush and Hoyt, 1981). Other families also contain predatory species useful in apple orchards (e.g. Trombididae,

Anystidae, Stigmaeidae and Tydeidae); however, these predators usually play a supporting role to the phytoseiids. In the mid-Atlantic area of the USA, a predatory coccinellid (*Stethorus punctum* (LeConte)) provides the greatest degree of biological control, whereas a related species in the western USA (*Stethorus picipes* Casey) plays only a minor role. Several groups of predatory bugs (especially mirids in the genera *Campylomma*, *Campyloneura*, *Blepharidopterus*, *Atractotomus*) will prey on mites and may play an important role in biological control. The relative dominance or contribution of a predator is governed by many factors, including climate, pest complex, surrounding habitat and spray regimes prevalent in the area.

19.4.1.2 Eriophyid mites

There are two basic groups of eriophyids, free-living and those causing plant deformities (galls or blisters). In the former category, the apple-rust mite, *Aculus schlechtendali* (Nalepa), is widely distributed and common, but rarely considered a serious pest. While high populations can cause leaf bronzing and premature terminal bud set (Hull *et al.*, 1986), it is considered a quasi-beneficial species in some areas in that it provides an alternative prey for predatory mites (Hoyt, 1969). Sensitive cultivars (e.g. 'Golden Delicious') may be russeted by feeding in the calyx area, which occurs shortly after bloom. Examples of the gall-formers attacking apple are few. Burts (1970) reported on two closely related species *Eriophyes* (*Phytoptus*) *pyri* (Pagenstecher) and *Eriophyes mali* (Burts), both of which may attack apple. They cause blisters on the leaves and fruit, leaving the latter scarred and deformed. The current spray programme has made these mites rare.

19.4.1.3 Leaf-miners

Several families of microlepidoptera (moths) mine apple leaves in the larval stage. The egg is laid on the surface of the leaf (usually the underside) and the newly hatched larva penetrates the leaf directly from the egg,

with no exposure on the leaf surface. The entire preimaginal period is spent in the mine, which is formed between the upper and lower epidermis by the larva's feeding activities. The shape of the mine is usually characteristic of the species or group: the gracillariid leaf-miners (*Phyllonorycter* (= *Lithocoletus*) *blancardella*, *Phyllonorycter elmaella*, *Phyllonorycter crategella*), or so-called 'tentiform' leaf-miners, produce a distinctive dome-shaped mine with white feeding specks visible from the upper leaf surface. Two species of Lyonetid moths (*Leucoptera malifoliella* (= *scitella*) and *Lyonetia clerkella*) produce a blotch and sinuous mine, respectively (Alford, 1984). Several species of coleophorid moth (case-bearers) also form mines, but these are usually minor pests.

The cryptic habit of the larvae presents some challenges for chemical control. Either the adult must be targeted with applications sufficient to cover the entire flight period or the pesticide must penetrate the leaf surface in order to deliver the toxicant to where the larvae are feeding. True systemic insecticides are now rare and, because of residue problems, few are being developed. Insecticides with translaminar activity are sufficient and typically present few problems in the registration process. While several effective insecticides are registered for use against leaf-miners, biological control has been reasonably well studied and partially implemented. Parasitic wasps (e.g. *Pnigalio flavipes*, *Pnigalio marylandensis*, *Apanteles ornigis*) are regionally abundant and can provide substantial levels of control. However, hymenopterous parasitoids, as a group, tend to be less tolerant of broad-spectrum insecticides, and biological control is easily disrupted.

19.4.1.4 Skeletonizers

There are several species of arthropods from various groups that skeletonize leaves, but none are specialists on apple and their significance is sporadic and local. Examples include the apple and thorn skeletonizer (*Eurtomula pariana*; Lepidoptera: Choreutidae) and the pear slug (*Caliroa cerasi*; Hymenoptera: Tenthredinidae).

19.4.2 Bulk leaf feeders

This is a varied group, comprised mostly of polyphagous Lepidoptera. Many are pests of deciduous forest trees, which can use apple as a host in the absence of pesticide residues. Examples include the notodontid moths *Datana ministra* and *Schizura concinna* and several species in the lasiocampid/lymantriid group (*Orygia antiqua*; *Euproctis chrysoheoa*, brown-tail moth; *Euproctis similis*). The winter moth (*Operophtera brumata*) is occasionally an important pest of apple in Europe. The autumn webworm (*Hyphantria cunea*; Arctiidae) is an example of a gregarious nest maker, which forms a large web (up to 50 cm long) and devours all leaf material inside it. Other gregarious lepidopterans include the tent caterpillars (*Malacosoma americana*, *Malacosoma fragilis* and *Malacosoma disstria*; Lasiocampidae) and the ermine moths (Yponomeutidae, e.g. *Yponomeuta malinellus* (apple ermine moth)); and others in the genera *Swammerdamia* and *Paraswammerdamia* are capable of using apple as a host. Currently, these are primarily pests on unsprayed back-garden trees, but they represent a rich pool of potential insect species that may respond to our changing pest-control regimes.

19.5 Structural Feeders

The group is defined as those attacking plant parts other than fruits and foliage, that is, branches, trunk and root systems. The group is a varied one taxonomically, and several of the pests included cross the damage-classification boundaries as defined here. While some of these pests can cause sufficient damage to cause tree death, as a group they are generally considered less important than the fruit and foliage feeders.

19.5.1 Superficial woody-tissue and shoot feeders

Two groups of Homoptera (scales and mealybugs) are widespread and sometimes important pests of apple. San Jose scale

(*Quadraspidiotus perniciosus* (Comstock)) is widely distributed and, left unchecked, can cause reduced tree vigour or even mortality (Plate 19.11). Scales feed primarily through tree bark, forming large encrustations that devitalize the tree. Mealybugs (especially Pseudococcidae) also suck plant juices, but usually choose more tender tissues (shoots and leaf axils) as feeding sites. In the latter case, the primary damage is not from removal of plant product, but rather the production of honeydew (liquid drops of excrement rich in simple sugars). Honeydew dripping on fruit can cause fruit russetting on sensitive cultivars or can support the growth of sooty mould, a superficial but unsightly fungal growth.

Both scales and mealybugs are considered to be induced secondary pests, which would occur only at low levels if their natural-enemy complex were not decimated by broad-spectrum pesticides. Currently, the pre-bloom use of horticultural spray oils appears to keep scales in check, although this activity is probably supplemented by in-season use of organophosphates. Mealybugs, on the other hand, can be extremely persistent once established (usually in large, older trees) and even an intense spray programme can only keep them in check, not eradicate them. Both species will infest the fruit towards the latter part of the season, especially when populations are high. A red ring appears around the scale that settles on fruit; mealybugs usually move to the calyx, where detection is difficult during packing operations. Feeding in the calyx end causes a softening and deterioration, which may be exacerbated by long-term storage. Quarantine measures and food contamination are issues with these two groups of pests.

The psyllids (Homoptera: Psyllidae) are key pests of pear, but one species, *Psylla mali* (apple sucker), is a corresponding pest of apple in some regions. Like pear psylla, this pest feeds on shoots and produces honeydew, with the attendant problems for fruit and vegetative growth. However, its importance on apples is minor in magnitude compared with the related species attacking pear.

Another large and important group of homopterans (aphids) may also be classed as

shoot feeders. This group has specialized in phloem feeding and is a large and successful group of pests on many crops. The aphids that feed on apple may use it as their only host or as the primary or overwintering host, with a different plant species as a summer host. The two life-history patterns have a definite influence on management.

Apple aphid (*Aphis pomi*) (Plate 19.12) is a widespread pest of apple, occurring in most apple-growing regions of the world. It spends its entire life cycle on apple, reproducing by parthenogenesis for the greater part of the season. Winged (alate) forms are produced under high population levels to colonize new host plants, and in the autumn sexual forms are produced, which mate and lay overwintering eggs. Both leaves and shoots are attacked, and some level of growth reduction is assumed under heavy attack; however, most of the concern for this pest involves the production of honeydew and sooty mould and the resulting fruit contamination.

Several other common aphid species are heteroecious, although their damage may be quite distinct from that of apple aphid. The rosy apple aphid (*Dysaphis plantaginea* or *Dysaphis devecta*) also feeds on shoots and leaves, but injects a salivary toxin, which severely deforms both organs. In addition, the toxin causes fruit deformity on sensitive cultivars. This pest colonizes a herbaceous weed host during the summer; thus control measures must occur fairly early in order to be effective. Woolly apple aphid uses elm as the alternative host in some areas, but is functionally monophagous in the north-western USA and Europe. This species produces both aerial and edaphic colonies; the former are easily controlled, the latter with great difficulty. The root colonies are thought to devitalize the tree and, even though rootstocks were developed specifically to be resistant to woolly apple aphid (the Malling Merton series), there is evidence that this resistance is breaking down. Feeding by both the root and shoot colonies produces galls; typically, the above-ground galls (which occur in leaf axils) are pruned off and are of little significance. Several species of *Rhopalosiphum* (*R. fitchii* and *R.*

insertum) are occasional pests of apple, using one of the *Gramineae* as their summer host. Only very heavy infestations, which can infest developing fruitlets, are considered damaging.

Aphids have a rich and varied natural-enemy complex that prey on them, including lacewings (*Chrysopa* and *Hemerobius*), coccinellids (ladybirds), various parasitic wasps and a variety of predatory mirids (e.g. *Campylomma*, *Deraeocoris*, *Orius*). Despite this, aphids often escape from biological control. Many of their predators are generalists and will only be attracted to large aphid populations (i.e. after the point where control is needed or desired). A number of broad-spectrum pesticides used in orchards are toxic to one or more of these natural enemies and disruption of biological control early in the season may preclude stable regulation for the rest of the season.

Woolly apple aphid (Plate 19.13) was one of the earliest targets (1920s and 1930s) of a widespread introduction of a biological-control agent, the parasitic wasp *Aphelinus mali*. This wasp was introduced in many of the areas around the world where woolly apple aphid had also been introduced and was successfully established in most areas (Yothers, 1953). It is still thought to provide the primary means of biological control today, although the generalist predators described above also play a role.

19.5.2 Wood-boring insects

Several families of Lepidoptera attack the cambium of the trunk and major scaffold limbs, and prolonged attack can girdle and kill these organs. The clearwing moths (*Sesiidae*) have several species that attack various fruit and ornamental trees and at least one species that infests apple (*Synathedon myopaeformis*; UK and continental Europe). One species of tortricid moth (cherry-bark tortrix, *Enarmonia formosana*) causes a similar type of damage.

While rarely a problem in sprayed orchards, these insects can be difficult to control once established. It is difficult, if not impossible, to kill larvae in their galleries

with pesticides; thus pesticidal control measures must be directed at the adults. Typically they are univoltine, with a prolonged flight, making continuous coverage a necessity.

The scolytid beetles comprise some of the more serious forest pests, and several species in the genera *Scolytus* and *Xyloborus* are pests of apple. The larvae form distinctive galleries in the wood, and adults often bore into shoots just below buds, causing weakening and breakage. In general, these insects are usually attracted to trees that are already weakened by some other pest or disease, although young trees can suffer damage when they are close to a source of emerging adults. Coleopteran wood-borers in the families Buprestidae and Cerambycidae may also attack apple, but are rare in sprayed commercial orchards.

19.5.3 Root-system pests

This is a fairly restricted group of pests, which are given little attention either because they cause only occasional damage or because of their cryptic life history. The larvae of scarab beetles (several species in the genera *Polyphylla* and *Pleocomma*) feed on roots and can be locally severe. Trees on sandy soils where the grubs thrive may suffer long-term damage; orchardists will often replant repeatedly, trying various combinations of fertilizer or watering to promote tree growth, when in fact the root system is being systematically destroyed.

Soil fumigation is currently the best remedy to allow trees sufficient time to establish before the beetles reinfest the orchard. Soil-applied pesticides are widely discouraged

because of groundwater contamination issues. While biological-control agents are known, their management is little studied or applied. Entomophagous nematodes (injected into the soil) may alleviate the problem, but their effect is not well studied in tree fruits.

One very large species of cerambycid beetle (*Prionis* sp.) can attack apple; control measures are similarly difficult. Weevil (curculionid) larvae are known to attack the root system on occasion, but the extent of damage is not well defined. The adults of some species may also be problematic when they feed on fruits, fruit stems or foliage.

Woolly apple aphid is the only truly ubiquitous root pest of apple (see above), although typically only the aerial colonies are treated.

19.6 Conclusion

Apple pest management is continually evolving in response to changing horticultural practices, the genetic structure of insect populations, the importation or re-emergence of new pests and societal pressures. These pressures encompass fewer and safer residues on food products, reduced environmental impact and the concept of sustainable agricultural production. The result has been increased regulation of pesticide use worldwide and incentive programmes (specialty labels) that promote reduced-impact pest-management programmes. With the globalization of fruit marketing, it is likely that all countries wanting to export apples will have to conform to production and pest-management practices that embrace these concepts.

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20 Apple-orchard Freeze Protection

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Apple production on a per-hectare basis has increased greatly over the past few decades. Earlier-producing, higher-yielding, high-density orchards of newer cultivars have made apple production a highly competitive business. Factors that have increased production have resulted in decreased or negative profit margins due to excess supply. In

such a severely competitive business environment, the successful apple grower must produce the maximum yields of quality fruit possible per hectare at the lowest possible cost in order to survive. In many fruit-producing areas, losses from freezes are substantial. In fact, freeze damage losses in apple orchards have exceeded the combined

losses to all pests. In this chapter we shall consider details of freeze protection for the apple orchard.

20.1 Site Selection

The best way to avoid freeze problems is to select a freeze-free site. Orchard-site visits with veteran orchardists, area fruit agents and professional pomologists can be very valuable for assessing freeze susceptibility. If apple trees are present, spur system anatomy can reveal their recent bearing history. Cluster-base enlargements that indicate fruit-production history can be observed for the last 5–10 years. Spur systems should have such cluster-base enlargements every other year if the area is a good freeze-free site (Fig. 20.1). If a new fruit area is to be developed, temperature measurement over a period of time is usually necessary to select a satisfactory site with confidence. Inexpensive data-loggers can be placed in temperature-monitoring locations in appropriate shelters on potential sites and data can be downloaded monthly. Temperatures should be accumulated for at least 24 months – longer if possible – so that accurate estimations of chill, anthesis and growing degree-day accumulations can be determined. Estimation of bloom dates for

apples can be made from the accumulated temperature data. Freeze potential can then be determined from the temperatures on each site during bud break, anthesis and full-bloom periods. Probabilities of advective and radiative freezes can be developed from a few years of accurate temperature data that appropriately represent the characteristics of a particular site. Approximations of the climate of potential fruit areas and long-term normals for existing weather stations may be obtained from state climatologists.

Good sites may have problem subsites. Small valleys with no outlet for air drainage, low spots in otherwise good orchard land and obstacles to air movement, such as wind-breaks, swales, borders, basins and roadways, often cause cold-air stagnation and freezes. These freeze-labile subsites can be used for alternative crops that tolerate low temperature during part of their production cycle or used for roadways, drainage or equipment- and bin-storage areas.

Other site considerations should be included in the analysis of each potential fruit-orchard area. The soil should be relatively rock-free, of medium texture, of neutral pH, of high water-holding capacity and fertile. The site is more important than the soil because the soil may be modified to advantage on a good site, but the best soil on



Fig. 20.1. Apple spur systems showing cluster-base enlargements where fruit were borne on every other year's growth in a productive orchard

a poor site will not allow profitable fruit production. Prevailing winds, often common in valleys and canyons, may help reduce freeze probability due to their ability to mix inversions. While windy sites may be advantageous for freeze prevention, they may be a hindrance to honey-bee activity, pollination, spray application and tree conformation. For additional information on the characteristics of a good site, see Chapter 11.

20.2 Cultural Practices

20.2.1 Soil

Fine-textured soils that are compact, full of water and devoid of surface insulation have greater heat adsorption and storage capacity than medium- or coarse-textured soils, soils with less water due to their lower water-holding capacity and soils with insulating mulch layers on their surfaces. When medium- or coarse-textured soils contain little water and large amounts of air, they contain less heat and are poor conductors of the heat they do contain. Often during winter, reoccurring freeze/thaw cycles cause soils to expand and develop numerous air spaces. Air spaces serve as insulators and decrease conductivity. Firming the soil with irrigation or other methods will decrease its insulation capacity. Other insulators at the soil/air interface are weeds, mulches, grass cover crops, chopped prunings or rubbish. Mowing or flailing machines can decrease the effect of these insulative layers on the soil surface and increase energy conductivity and radiation. Uninsulated, water-filled, southerly-exposed soils (in the northern hemisphere) will accumulate significantly more energy than insulated, air-filled, north-aspect soils.

20.2.2 Orchard canopy

Modern high-density orchards of small trees often incur problems with air flow. Trees that are planted close together impede the flow of cold air through and out of the orchard. Whenever possible, trees should be planted with the hedgerows or multiple-tree beds

orientated to allow air drainage down-slope. Channels should be maintained in natural low areas to encourage cold air flow through such areas and away from the orchard. Small trees also have the inherent problem of occupying the coldest part of an inversion-temperature profile. Older orchards with taller trees and wider alleyways allow more air flow out of the orchard and occupy space higher in an inversion.

20.2.3 Tree condition

20.2.3.1 Irrigation

Irrigation should be used to avoid tree stress during the late summer and autumn when tree maturation and acclimatization occur. Inadequate irrigation will stress trees through drought and excessive irrigation will limit root respiration due to lack of oxygen. Irrigations should be timed to fill the root profile with adequate water for the trees' needs, but to avoid waterlogged soils that limit root respiration and growth. Trees should not be stressed by limited water late in the season to 'harden' them. Such stress will generally result in more limited cold-hardiness levels developing during the ensuing winter season. After trees have matured vegetatively and leaves have abscised, the soil should be filled to field capacity to ensure water availability through the winter. In drought conditions, winter irrigation is advisable.

20.2.3.2 Nutrition

Nutrition of apple trees should be maintained at optimum levels during the growing season. Nitrogen should be applied in early spring, just before root growth commences, and adequate supplies should be applied to give optimum shoot and fruit growth without supplying excess. Avoid late applications that will delay late-summer maturation and hardening of the trees. Growers are encouraged to use foliar analysis of critical orchard nutrients so that their fertilizer applications can be made in a timely manner and adequately (see also Chapter 12).

20.2.3.3 Pruning and training

Pruning and training of apple trees should be done in the dormant season and in the summer so that tree response will not produce late-season, succulent, tender wood. The general rule is to avoid pruning from dormancy induction in late summer through the ensuing autumn and early winter period (Plates 20.1 and 20.2).

20.3 Energetics of the Orchard Environment

Energy is transferred in the orchard environment by radiation, conduction, convection and latent-heat transfer. These processes are operative in any freeze event in the orchard and should be thoroughly understood.

20.3.1 Radiation

Radiation is energy transfer by radiant energy or electromagnetic waves. Most radiation in our solar system originates in the sun. Radiation waves travel through space and do not need molecules to facilitate their movement. This energy includes infrared, visible and ultraviolet rays ranging from 1 millionth to 10 millionths of a metre in length – often called short-wave radiation. Short waves have greater energy than longer waves, but they all travel at the speed of light. The earth also emits radiation, but, since the earth's temperature of 288K (15°C, 59°F) is much cooler than the sun's temperature of 6000K (5815°C, 10,500°F), it emits weaker radiation 10 millionths to 20 millionths of a metre in length – often called long-wave radiation. Through a balance between interception and emission, the earth reaches a radiative equilibrium temperature. The earth is 150,000,000 km (93,000,000 miles) from the sun and turns once a day, so its equilibrium temperature without an atmosphere would be about 255K (–18°C, 0°F). However, with its atmosphere, the actual average earth-surface temperature is 288K (15°C, 59°F).

This higher average temperature is mainly due to the atmospheric absorption of energy. Other important selective absorbers on the earth's surface that contribute to temperature modification include ice, snow, water vapour and carbon dioxide. A simplified earth/atmosphere/solar energy balance is given in Fig. 20.2.

20.3.2 Conduction

Conduction is energy transfer from molecule to molecule. A nail held in the hand seems to be cool to the touch because iron has high heat conductivity. When a nail is held by the fingers on one end and in a flame on the other end, it soon becomes warm to the touch by molecular motion or conduction. Wood, as in a wood match, does not have a high heat of conductivity and can support a flame on one end and still be held by the fingers. Heat conductivity, or the ability to conduct heat by molecular motion, of some common substances is presented in Table 20.1.

20.3.3 Convection

Convection is heat transfer by mass movement of a fluid, such as oil, water or air. Fluid particles having different temperatures and therefore different densities move freely to develop currents. On a sunny, warm, summer day, the major impact of the sun's radiation is received by the earth's surface. The surface temperature rises during the day and air next to the surface absorbs energy and expands by conduction of molecule-to-molecule energy from the surface. This warmed, expanded air becomes more buoyant than the air above it and rises. Cooler air displaces the warmed air and in turn absorbs thermal energy and also rises. The cycle is repeated to set up convective currents of rising warm air, called thermals. When horizontal motion occurs, the air movement is called a breeze or wind. The appropriate term for horizontally moving air with associated water vapour and other inclusions is advection.

The earth/atmosphere energy balance

Approximations - relative size of numbers indicates energy flux in and out of earth and atmosphere

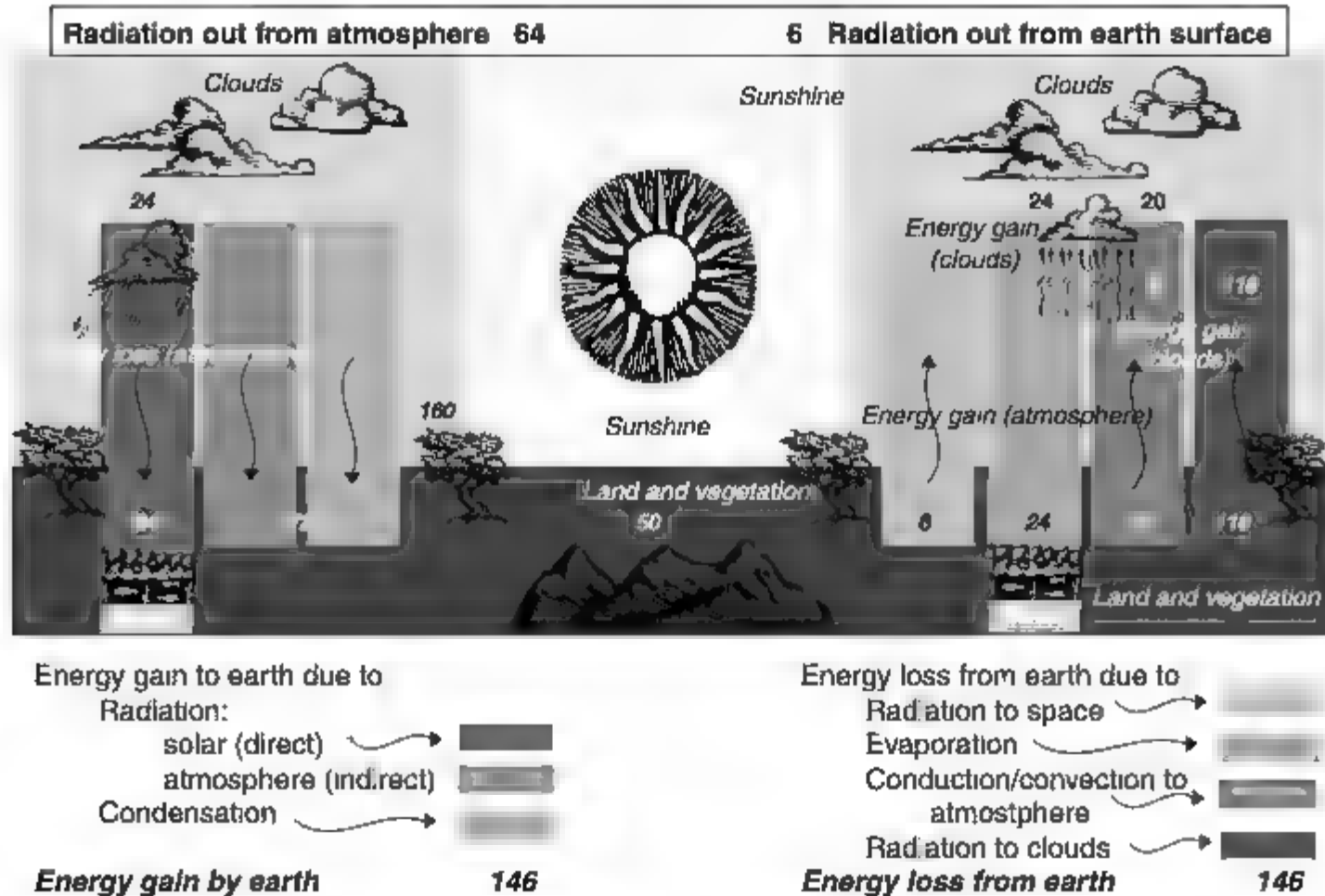


Fig. 20.2. Simplified earth/atmosphere/solar-energy balance. Numbers indicate magnitude of energy fluxes in the system. Most important energy fluxes are indicated.

Table 20.1. Heat conductivity of selected substances.

Material	Conductivity (cal s ⁻¹ cm ⁻² °C ⁻¹)
Air at 20°C	0.00006
Dry soil	0.0006
Water and snow	0.0014
Wet soil	0.005
Ice (0°C)	0.005
Rocks	0.006
Iron	0.160
Silver	1.1

20.3.4 Latent heat

Latent heat is energy that is transferred when there is a change of state. Water exists in solid (ice), liquid (water) and gaseous (water vapour) states. When heat is applied to ice, the ice melts and the energy applied

goes into the water and becomes latent heat. When the reverse happens, the latent heat is released into the environment. The heat change for ice formation is called the heat of fusion and amounts to 80 cal g⁻¹ of water frozen. Thus, 80 calories are given off when the molecules in 1 g of water freeze

to become arranged with less molecular motion into ice crystals. As long as the ice/water phase transition occurs, heat is evolved and the temperature of the system will remain at 0°C. When all water is frozen, heat production ceases. The molecular motion returns on thawing, with energy absorption. A similar absorption or release of thermal energy occurs when water evaporates (absorption) or condenses (release). The energy involved in the latent heat of evaporation is the absorption of about 600 cal g⁻¹ of water. Conversely, when a 1 g of water condenses in the atmosphere, the latent heat of condensation results in the release of 600 calories. The heat of condensation is 7.5 times the heat of fusion! Large amounts of water are contained in the atmosphere, and the latent heat capacity of atmospheric water is an important source and sink for energy. The evaporation of water from equatorial regions removes energy from those areas. Water-laden air moves advectively towards the poles, where the water condenses and releases energy. These processes are tremendously important in the energy balance, advection and the prevailing winds of the turning earth. They are also important in the orchard environment when a freeze event occurs.

20.4 The Daily Thermal Cycle

The daily temperature cycle in the orchard typically, but roughly, traces the thermal influence of the short-wave insolation from the sun to the earth during the day and the long-wave radiation from the earth's surface during the night. During the day, an insignificant amount of the total energy from the sun showers the earth and its atmosphere. But the magnitude is insignificant only when compared with the total energy emitted from the sun. This miniscule amount of the sun's energy is highly significant to life on earth and is the source of nearly all of the earth's energy. In fact, the energy reaching the earth is sufficient to produce the equivalent of 5000 t of coal s⁻¹ in photosynthate. Of the total incoming solar

radiation – insolation that enters the earth and its atmosphere – only about 50% reaches the earth's surface, some directly and some diffusely or scattered from the atmosphere. About 4–6% is reflected from the earth's surface and 6% is reflected from the atmosphere. When clouds are present, up to 20% is reflected by water vapour. Depending on atmospheric conditions, the most important being water in clouds, up to 20% is absorbed by the atmosphere.

As the sun rises above the morning horizon, its energy is spread over a large area since it hits the round earth surface at a very low angle. As the earth turns, the impact angle changes and the energy concentration reaching the surface per unit area increases until solar noon. After noon, the reverse scenario occurs until the sun sets below the horizon. Thus, the energy curve through the day resembles a cone (Fig. 20.3a). However, the temperature during the day depends on more than insolation. The earth, too, is radiating energy from its surface proportional to the surface temperature. Surface temperature is highest in the early afternoon because, even though the intensity of incoming solar radiation decreases after noon, incoming energy still exceeds outgoing surface heat energy for a few hours. This energy contributes to the typical lag between the time of maximum solar radiation at noon and the maximum air temperature in an air thermometer several feet above the ground in the afternoon (Fig. 20.3b). At the time of the highest daily temperature, the air temperature is highest at the surface and decreases with increasing elevation (Fig. 20.3c). After sunset, diffuse radiation energy has a small impact for a short time, but its effect is small when compared with the long-wave radiation from the earth's surface.

Other insolation/radiative effects may be significant in the orchard microclimate. Hillsides, ledges, very large structures and large bodies of water may serve as reservoirs for thermal energy and reradiate that energy after sunset and during the ensuing night.

Conduction of energy from the soil surface or plant canopy to the adjacent air during the daytime warms the air and increases its buoy-

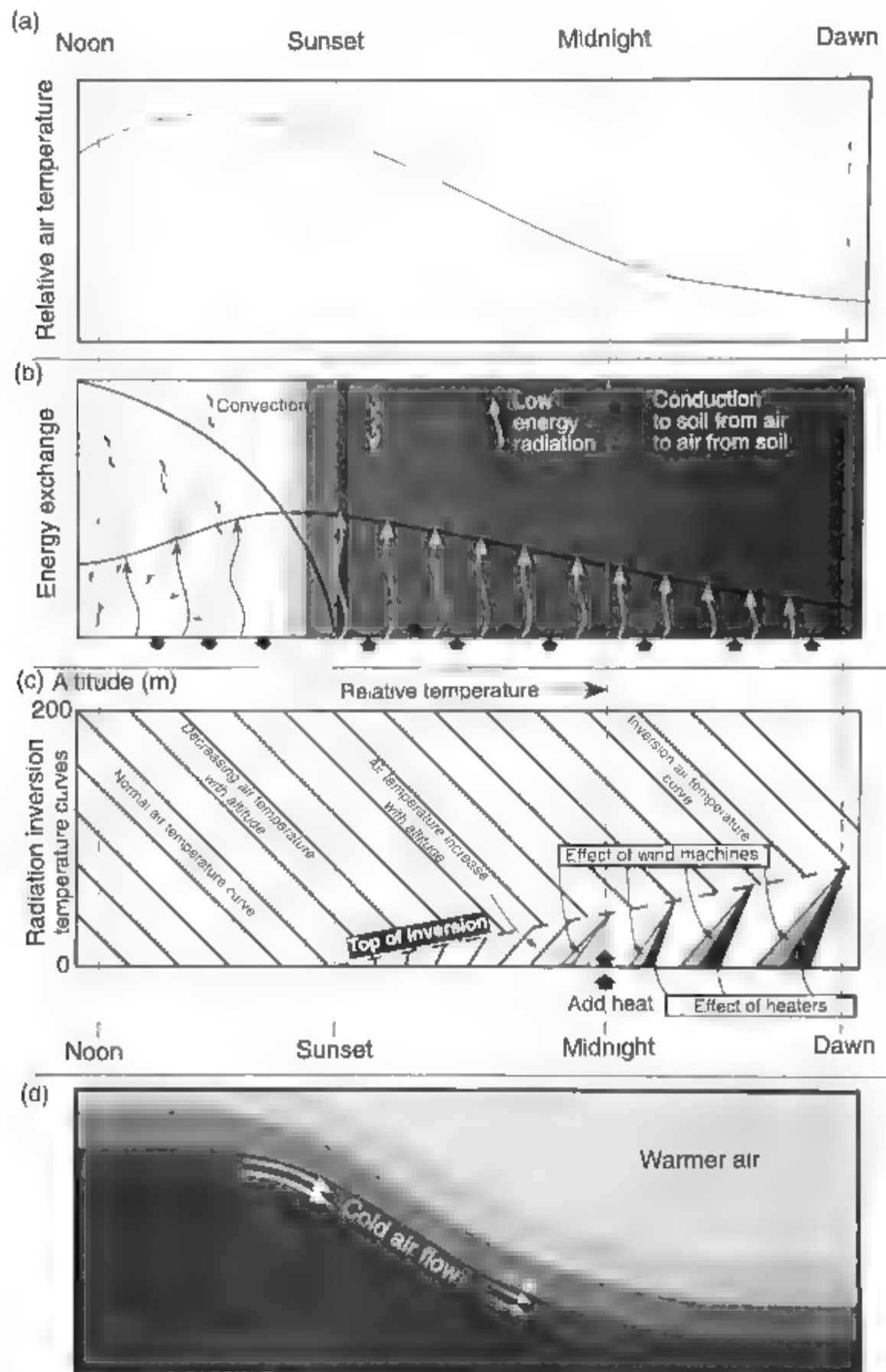


Fig. 20.3. Energy changes in the orchard environment from solar noon until the next dawn. (a) Air-temperature changes. (b) Incoming and outgoing radiation exchange, along with convection and conduction of energy into the soil during the day and conduction of energy from the soil to the adjacent air and outgoing radiation during the night. (c) Air-temperature profiles through the afternoon and night from the surface to an elevation above the top of the developing inversion. Triangles show the effect of wind machines and heating on the inversion-temperature profile. (d) Inversion created by cold air flow.

ancy The warmed air rises in convective currents through the daytime hours and into the night from thermal reservoirs. However, rising

thermal energy in buoyant air (due to less dense air and lessening pressures at higher elevations) does not significantly affect the

normal temperature gradient from warmest at the earth's surface to lower temperatures at higher and higher elevations above the surface. Clouds of water vapour reflect solar radiation into space and also reflect radiation from the earth's surface back towards the surface. The water-vapour content of the air is very important in temperature changes, since it is the main reservoir of atmospheric thermal energy. During the day, all methods of heat transfer are operating to develop the normal daytime temperature gradient, with the highest temperature at the surface and decreasing temperatures at increasing elevations.

Through the night, the surface of the earth cools by radiation to space (Fig. 20.3c). In the absence of short-wave incoming radiation and as the surface cools, energy from the adjacent air and soil is transferred to the surface and this energy is, in turn, radiated to space. This process continues during the night. The air temperature near the earth decreases and reaches a low just after sunrise, when outgoing radiation still exceeds incoming radiation. It is important to note that the daily low temperature occurs just after sunrise for this reason.

The normal temperature gradient during the day is warmest at the surface and cooler at increased elevations above the earth's surface. During the night, incoming radiation is very low and outgoing long-wave radiation from the surface and conduction of energy from relatively warm air near the surface to the surface, with subsequent radiation of that energy to space, set up a temperature gradient in the lowest few hundred feet of the atmosphere. The temperature becomes cooler at the surface and increases with elevation to a higher temperature. Above the elevation with the highest temperature, the temperature decreases again, as it did during the day. Since this gradient near the surface is the inverse of what it was during the day, the phenomenon is called an 'inversion'. An inversion results in a reservoir of warmer atmosphere above the orchard that may be located from just a few feet to several hundreds of feet above the surface. The elevation of the warmest air is called the 'top' of the inversion. This reservoir of warm air can be used in orchard freeze protection by mixing it

with cooler surface air. Inversions also form through the flow of cooler air near the ground into low areas (Fig. 20.3d).

20.5 Energy Changes in the Orchard Canopy

Air does not hold as much energy as the water in the air. The molecular weight of dry air (78% N_2 , 21% O_2 , 1% Ar plus small amounts of other gases) is about 29 g (= an ounce) and has a volume of 22.4 l (5.1 American gallons) at standard pressure and temperature. Energy changes due to molecular motion of atmospheric gases are very small on a molar basis, but, since the atmosphere of the earth weighs about 5600 trillion t (the weight of air above 1 ha at sea level is approximately 104,000 t – equivalent to about 42,000 t acre⁻¹), energy changes over large areas and in large masses, such as the area over an orchard, become very significant. When water vapour is added to the air and displaces the 'average' air molecule, the volume of air containing water becomes lighter because the molecular weight of water (18 g) is 11 g mol⁻¹ lighter than the average molecular weight of air (29 g). Therefore, water-laden air tends to rise. More importantly, the energy-holding capacity of the more humid air is significantly increased. At 25°C under normal pressure, water-vapour-saturated air holds 23 g m⁻³ of water. A 'box' of such air above an orchard 100 m high would contain about 21,000 kg of water ha⁻¹ (~16,000 lb. acre⁻¹). Due to its energy content, especially during phase changes, water in the air is very important in energy exchanges between the environment and the plant. Energy relationships of water in air are given in Table 20.2.

20.6 Water in the Orchard Atmosphere During Freezes

Water in the air stores large amounts of thermal energy compared with the air itself. The water status of the atmosphere is described in several ways. The most important is relative humidity.

Table 20.2. Water status and energy exchange (arrows indicate changes in temperature or state of water)

Energy given off by water		Energy taken up by water	
Water vapour in hot air			
+ 1 cal g ⁻¹ °C ⁻¹ Cooling -----	↓ ↑ -----	Heating	-1 cal g ⁻¹ °C ⁻¹
Water vapour in cool air			
(+ 600 cal g ⁻¹ °C ⁻¹ Condensation ----	↓ ↑ -----	Evaporation	-600 cal g ⁻¹ °C ⁻¹)
Deposition + 680 cal g ⁻¹ °C ⁻¹ {	Water at the dew/frost point }		680 cal g ⁻¹ °C ⁻¹ Sublimation
(+ 80 cal g ⁻¹ °C ⁻¹ Fusion -----	↓ ↑ -----	Melting	-80 cal g ⁻¹ °C ⁻¹)
Water as ice			
+ 0 cal g ⁻¹ °C ⁻¹ Cooling -----	↓ ↑ -----	Warming	-0 cal g ⁻¹ °C ⁻¹

where: Condensation = vapour to liquid
Evaporation = liquid to vapour
Fusion = liquid to ice
Melting = ice to liquid
Deposition = condensation and fusion
Sublimation = melting and evaporation

20.6.1 Relative humidity

Relative humidity is the percentage of the actual water-vapour pressure in the air compared with the saturation vapour pressure for that temperature, or the amount of water the air holds compared with what it can hold.

Water in the atmosphere serves as a temperature buffer when it is present, due to its energy-holding capacity relative to that of the air, its molecular vibrational and rotational energy and its latent heats of condensation/evaporation and fusion. During the night, humid air will absorb radiated energy from the earth's surface and radiate it back. Low-humidity air allows more energy to be lost to space. As the air temperature drops under humid conditions, the energy stored in water is released into the atmosphere at the rate of 1 calorie g⁻¹ of water °C⁻¹ and moderates temperature drop. Under dry air conditions, little radiation is absorbed and little heat is given up to the atmosphere, resulting in a more rapid and extensive temperature drop.

20.6.2 Dew-point/frost point

The dew-point/frost point of the air is the temperature to which the atmosphere must

be cooled, without changes in pressure or water-vapour content, to bring the system to water-vapour saturation. At the water-vapour saturation point, or dew-point/frost point, water condenses as liquid water (condensation) or deposits as ice (deposition). Dew forms if the temperature at which this occurs is above 0°C and ice forms when the temperature is at or below 0°C. The effect of condensation and deposition moderates temperature changes in the system. In the absence of incoming radiation energy, the temperature decrease will be relatively rapid to the dew-point/frost point. Below the dew-point/frost point, energy is released into the atmosphere from the condensation energy given off by water and the rate of temperature fall is much slower. Growers are encouraged when they find they have a high dew-point in the evening before a potential freeze, because they know that the atmosphere has a high water content and therefore contains much latent energy that will be used to moderate temperature fall. In contrast, if the dew-point is below freezing (i.e. at the frost point), atmospheric temperature will drop rapidly to that point, with relatively little energy release. Temperature fall at the frost point will be moderated by the release of the energy of fusion. But, since the temperature fall may be rapid to a tempera-

ture below the critical temperature, damage may occur. This is illustrated in Table 20.3, which illustrates two freezes that occur with different amounts of water in the air and, thus, different dew-points.

In freeze A, a high-dew-point freeze, a total of 689 cal g⁻¹ of water in the air would be released before the temperature reached the flower's freezing-point. The most important thing to note is that saturated air in freeze A contains over twice the water and releases about 120 times (5.64 g of water × 689 calories = 3886 calories m⁻³) as much energy by the time the temperature reaches the critical point than is released in freeze B.

In freeze B, a low-dew-point freeze, a total of 12 cal g⁻¹ of water in the air would be released before the temperature reached the critical flower freezing-point and subse-

quent energy release would be ineffective in preventing flower freezing. Freeze B is difficult to protect against because only 32 calories (2.67 g of water × 12 calories = 32 calories m⁻³) of energy are released from water per cubic metre in the air above the critical temperature. More energy is released at the ice-formation point of -8°C (18°F), but it is released after the flowers have frozen.

The heat exchanges illustrated in the two freeze situations are approximations only. The situations are actually much more complex. For instance, dew and ice formation result in changing relative humidities and dew/frost points. These changes result in changes in subsequent dew/frost formation and deposition temperatures so that release of heat would occur over a range rather than at a point during temperature fall.

Table 20.3. Temperature, water (vapour/dew/ice) and energy relationships in high (A) and low (B) dew-point freezes

Temperature		Water form		Energy release °C ⁻¹ g ⁻¹ (calories)	
°C	°F	Freeze A	Freeze B	Freeze A	Freeze B
10	50	Vapour	Vapour	+1	+1
9	48	Vapour	Vapour	+1	+1
8	46	Vapour	Vapour	+1	+1
7	45	Vapour	Vapour	+1	+1
6	43	Vapour	Vapour	+1	+1
5	41	Vapour	Vapour	+1	+1
4	39	Vapour	Vapour	+1	+1
3	38	Vapour	Vapour	+1	+1
2	36	Dew	Vapour	+600	+1
1	34	Dew	Vapour	+1	+1
0	32	Ice	Vapour	+80	+1
-1	30	Ice	Vapour	0	+1
-2	28	Ice	Vapour	0	+1
-3	26	Ice	Vapour	0	+1
-4	25	Ice	Vapour	0	+1
-5	23	Ice	Vapour	0	+1
-6	21	Ice	Vapour	0	+1
-7	19	Ice	Vapour	0	+1
-8	18	Ice	Ice	0	+680
-9	16	Ice	Ice	0	0
-10	14	Ice	Ice	0	0

Freeze assumptions:

Critical temperature at full bloom = -2.2°C (28°F)

High-DP freeze A conditions = 10°C DB, 6°C WB, 59% RH, 2°C DP, 5.64 g m⁻³ H₂O

Low-DP freeze B conditions = 10°C DB, 2.5°C WB, 28% RH, -8°C DP, 2.67 g m⁻³ H₂O

DB, dry bulb; WB, wet bulb; RH, relative humidity; DP, dew-point.

20.7 Freeze Types

The Glossary of Weather and Climate of the American Meteorological Society (Geer, 1996) defines a freeze and categories of freezes as:

The condition that exists when, over a widespread area, the surface temperature of the air remains below freezing 0°C (32°F) for a sufficient time to constitute the characteristic feature of the weather. A freeze is a term used for the condition when vegetation is injured by these low air temperatures, regardless if frost were deposited. Freezes may be classified as *light freeze* (little destructive damage, except to tender plants); *killing freeze* (widely destructive to vegetation, effectively terminating the growing season); and *hard freeze* (staple vegetation destroyed).

Freezes can also be characterized as advective or radiative. In an advective freeze, large masses of air, which may have widely varying dew-points, are carried into the orchard by wind. The advective freeze may or may not include clouds. A radiative freeze develops when skies are clear, dew-point results in frosts and winds are absent or light. Often a freeze may be a combination advective/radiative event. The advective freeze is carried into the orchard by winds; then, after the winds and clouds associated with the advection subside, radiative processes occur to produce a radiative freeze.

Another classification of freezes depends on the time of their occurrence. Orchards may be damaged in autumn freezes. Autumn freezes can be hazardous after conditions that delay tree hardening, such as after autumn pruning, under fertilization practices that result in growth late in the autumn, or when tree foliage has been damaged, resulting in decreased photosynthesis before or during the hardening period. Trees may be damaged in winter freezes when extremely low temperatures occur that exceed the low range for the species or developmental stage. Autumn and winter freezes may occur in the south-west side (northern hemisphere) of tree trunks and scaffold limbs, due to rapid temperature changes in tissue directly exposed to the sun during late afternoon. The rapid change from an elevated temperature to a freezing temperature at sundown is an exten-

sive and dynamic change that frequently causes damage. Energy reflectants applied to the south-west side of the tree trunk and scaffold limbs prevent this south-west winter injury. Late-winter freezes may occur when buds are still relatively hard before appreciable hydration and bud swell has started. Spring freezes can occur at increasingly higher temperatures due to acclimatization accompanying increasing bud hydration and metabolic activity. Buds are most susceptible to freezing at full bloom when maximum hydration has opened the flower and tender flower parts are fully exposed to ambient conditions. Critical flower-bud temperatures for apples are given in Table 20.4.

20.8 Monitoring Freezes

Electronic technology makes it possible today to instrument and monitor various meteorological facets of the orchard with solid-state devices coupled with computers. Temperature-sensing thermocouples should be placed in representative locations vertically and horizontally and in the warmest and coldest areas of the orchard (Plate 20 3). In addition, each block of trees that may respond differently to temperature should be monitored. These can be interrogated by the computer every few seconds and various software packages can provide continuous read-outs of each location's temperature. National weather services often provide critical information for orchardists. In the USA, the National Weather Service (NWS) forecasts minimum temperatures over large areas. These temperatures are for standard thermometers 1.5 m above the ground in standard NWS instrument shelters. The NWS provides frost warnings when the temperature is predicted to be near 0°C with winds less than 16 km h⁻¹ (10 m.p.h.), frost/freeze warnings when the temperature will go below 0°C with winds less than 16 km h⁻¹ and freeze warnings when the wind speed is predicted to be above 16 km h⁻¹ with temperatures below 0°C. These warnings are estimates for NWS locations and are of limited help to the grower. Orchardists need specific weather informa-

Table 20.4. Critical temperatures for apple buds during anthesis. Temperature for 10, 50 and 90% mortality (°C/°F).

Bud stage ^a	Mortality		
	10%	50%	90%
Post-dormant			
No swelling	< -9.4/15.1	< -8.9/15.9	< -17/1.4
Silver tip	-9.4/15.1	-8.9/15.9	-17/1.4
Green tip	-7.8/18.0	-8.9/15.9	-12/10.4
Half-inch green	-5.0/23.0	-5.6/22.0	-9.4/15.1
Tight cluster	-2.8/27.0	-3.0/27.0	-6.1/21.0
First pink	-2.2/28.0	-2.8/27.0	-4.4/24.0
Full pink	-2.1/28.0	-2.2/28.0	-3.9/25.0
First bloom			
King	-1.7/29.0	-2.0/28.4	-3.8/25.0
Laterals	-2.2/28.0	-2.2/28.0	-3.8/25.0
Full bloom	-1.7/29.0	-2.0/28.4	-3.8/25.0

^aBud stage refers to average bud stage. Bud populations consist of some buds ahead and some buds behind the average bud stage. This population effect produces the critical temperature range. Time is also a factor; the longer a bud population is at or below the critical temperature, the more buds will succumb to freezing.

tion for each different area in their orchards and should instrument their plantings to obtain the information required for various cultural purposes.

Air temperature is the most critical meteorological variable to monitor during freeze events. Air temperature is usually indicative of bud- or flower-tissue temperature, but it can vary slightly due to radiation balance. Therefore, in addition to sheltered thermocouples, a grower may want to place small thermocouples closely adjacent to or in buds or flowers to determine their actual temperatures.

Radiative and advective freezes occur in almost every orchard every year. To monitor radiative freezes, a tower of at least 10 m should be erected within the block of trees with sensors located on it to measure temperatures and monitor the inversion strength. Two 76 mm (3 in) × 6 m (20 ft) sections of schedule 40 polyvinyl chloride (PVC) pipe, coupled together and guy-wired for support at 6 and 12 m, can be used successfully for a 12 m (40 ft) tower. Thermocouples are placed at 2 m intervals on the tower. Thermocouples need to be

sheltered from the sky with inexpensive plastic-foam cups (Fig. 20.4). Of course, a short tower such as this is not as good as a taller tower, but it can give valuable information to the grower about the air temperature in the bottom layers of inversions and an estimate of the inversion strength. It is also possible to use tethered, instrumented helium balloons to monitor inversions under calm conditions, but the need to reel the balloon up and down to obtain temperatures at different elevations is time-consuming. Archives of temperature characteristics of inversion events over a few seasons can be used to create computer programs that can be used to predict radiative-freeze temperature changes through the night as a guide in crop protection.

Another critical meteorological variable that affects temperature change and needs to be monitored is the amount of water in the air or the relative humidity. Temperature drop in the orchard during a radiative freeze is dependent on heat lost from the surface during the night. Water in the air modifies temperature changes; therefore, monitoring water in the atmosphere is



Fig. 20.4. Sheltered (plastic-foam cups cut in half, thermocouples on a 4 m tower.

very important, because it will reflect the heat energy available to moderate temperature fall. Clouds, for instance, create a thermal blanket for the orchard. When clouds are present, they create a greenhouse effect and contain energy in the atmosphere. Very thin clouds as high as 10,000 m can create this effect

When clouds are not present, humidity needs to be monitored to provide a reasonable estimate of the rate of temperature fall. A psychrometer (a hygrometer consisting of two similar thermometers, with the bulb of one kept wet, so that the cooling that results from evaporation makes it register a lower temperature than the dry one, and with the difference between the readings constituting a measure of the wetness of the atmosphere) can be used to determine the dew-point. The dew-point is important in the rate of temperature fall. At the dew-point, energy

from the heat of condensation (stored or latent heat) is released. This heat, when added to the atmosphere, decreases the rate of temperature fall significantly. Above the dew-point, temperature fall is relatively rapid, but, after dew formation begins, the temperature fall is relatively slow. If the dew-point is significantly above the critical temperature, there is little danger of a critical freeze, but, if the dew-point is near or below the critical killing temperature of flower buds, the temperature will drop rapidly into the critical area and protection will be needed.

Significant advantages accrue to growers who educate themselves in meteorology and use historical records and current temperature and dew-point monitoring to estimate critical temperature probabilities to predict potential freezes in their blocks of trees. There are custom forecasts available, but, even when they are accurate, they are not as good as continuous monitoring of the meteorological variables that affect temperature fall in a specific orchard during potentially hazardous freeze nights.

20.9 Methods for Freeze Protection

20.9.1 Heating

Orchards have been heated during freezes with anything that would burn. Prunings, firewood, tyres, coal, oil, diesel, charcoal, coke, paraffin, solid petroleum, liquid petroleum, propane and many other materials have been used. Systems have progressed from open fires on the orchard floor, to metal pots, to baskets in trees, to return-stack heaters, to specialized high-radiative-output heaters fed by underground fuel lines connected to underground tanks. Individual heaters (up to 100 return-stack heaters and 150 pressurized-propane heaters ha^{-1}) can be located throughout the orchard to obtain the desired heat distribution (Plate 20.4). Many small heaters spread throughout the orchard to allow uniform heating under various air flows and site characteristics are much better at maintaining temperatures above the critical freezing-

point than just a few larger heaters. Large heaters can release enough heat to create a chimney effect through the top of the inversion, with heat losses near the ground. However, large heaters can be used under wind machines in a situation where the rising heat plume is distributed horizontally through the orchard by the wind machine. Usually heaters are more concentrated on the orchard borders, especially on the windward side. The pipeline-fed systems have many fixed heaters per acre that are not readily moved from place to place so that the optimum arrangement of heaters for the most characteristic freeze conditions must be made at the time of installation. Pumps, filters, pressure controls, automatic lighting devices, pilot lights, specialized nozzles and computer control are components that characterize the most elaborate systems. The cost of return-stack oil heaters is around US\$2600 ha⁻¹. Pressurized propane heaters, including some to heat the storage tank, along with the service equipment mentioned, may cost from US\$6200 to US\$10,000 ha⁻¹.

Most commercial heaters and home-made heaters from surplus shell casings emit the majority of their heat as convective heat and thus they are very effective under inversion conditions. However, these heaters do not perform as well under advective conditions as heaters having a high radiative output. Some heaters – for instance, coke heaters that produce ~40% of their heat as radiant heat – have a greater effect on bud temperature under advective conditions, since radiation is not disturbed by winds.

The combination of heaters and wind machines, which allows mixing of an existing inversion with heat additions within the inversion, has been successful. Increases in fossil-fuel costs have made most systems obsolete. However, wind machines and heaters can be used for citrus-orchard protection, where the goal is not only to save the current fruit crop but also the orchard itself. The combination can also be used in blocks of high-density, high-value deciduous orchards to save the trees during severe winter freezes or to ensure a crop for specific lucrative retail markets.

20.9.2 Overhead irrigation

The temperature of an ice/water coating on trees remains very close to 0°C. Ice build-up results in much more ice than water on the tree, with the water in a thin surface film. Water is added rapidly enough with overhead sprinklers to form small clear icicles, which remain covered with a thin water film. Icicles may form in arcs due to the changing load on the limbs. Ice with entrapped air, which appears white, indicates that water is not being added at a sufficient rate to maintain a constant ice/water coating. Sprinkler heads should be of a design that will continue to rotate with ice build-up. Gravity sprinkler systems are efficient, but pumped systems in which the pressure can be increased are better, since they can provide variable water-application rates. Ice/water encasement of apple trees before and at full bloom has been used successfully for many years. It is not used after full bloom because encasement of foliage associated with shoot growth results in excessive ice build-up and may damage tree structure. Smaller trees trained to central-leader systems, such as the Pacific Northwest central leader, Hytec, slender-spindle and vertical-axis systems, easily withstand the load of ice encasement. Open-centre trees do not tolerate ice loading as effectively as central-leader trees.

Significant quantities of water are used for ice/water-encasement freeze protection (Fig. 20.5). Soils subjected to water saturation during this procedure should be adequately drained so that root function will not be impaired due to water accumulation or low soil temperatures. Irrigation systems used for ice encasement for freeze protection should be installed following standard irrigation design principles, but they should be over-designed to allow sufficient rates of water application to protect against freezes down to about -8°C (18°F). The system should be capable of applying up to 1.2 cm h⁻¹ for freezes near the critical temperature of the green-tip bud stage of -8°C (18°F) to the critical temperature at full bloom of -2°C (28°F). Sufficient water must be readily available to continue the sprinkling until all ice has melted.



Fig. 20.5. Ice build-up from sprinkler overhead irrigation.

During a freeze, the ice/water-encasement sprinkler system should be started at a temperature several degrees above the critical to avoid possible killing temperatures due to evaporative cooling on system start-up. Since the heat of fusion of water on freezing is 80 cal g^{-1} and the heat of vaporization associated with evaporation is 600 cal g^{-1} , the evaporation of 1 g of water absorbs the heat equivalent to the freezing of 7.5 g. Winds and the relative humidity of the air influence the evaporation rate, but relative humidity is modified greatly as soon as sprinkling is initiated. Therefore, the forecast minimum temperature and wind speed are critical in determining the rate of water application. If the forecast temperature minimum is below the protection capacity designed into the system, the system must not be started because severe damage can result. Wind speeds of 3 m s^{-1} require more than twice the amount of water for protection as that needed for winds of 0.5 m s^{-1} . At low wind speeds, as temperatures drop from -2 to -8°C (28 to 18°F) – about the practical limit for ice encasement protection – water requirements increase approximately $0.1 \text{ cm h}^{-1} ^\circ\text{C}^{-1}$.

Ice/water-encasement-use decisions need to incorporate the critical temperature, the forecast minimum temperature in the orchard, the wind speed, the dew-point and the water-delivery capacity of the system.

20.9.3 Under-tree sprinkling

Several apple growers have reported success with under-tree sprinkling for freeze protection. Large experiments in Utah (USA), using elaborate statistical designs, in a tart-cherry orchard in the spring seasons of 3 different years gave no positive results (Plate 20.5). Of course, the high mountain desert with its low humidity would be expected to result in high evaporative cooling and, indeed, the only significant temperature differences were negative. Others, however, have reportedly used under-tree sprinkling successfully for freeze protection. Orchardists in the Casa Grande area of Mexico use 21°C (70°F) well water to protect their orchards and report success. It has also been reported that orchardists in Washington State (USA) have used heated water to provide under-tree sprinkling for freeze protection in their orchards.

20.9.4 Wind machines

The climatology of a site must be analysed to determine the incidence of advective and radiative freezes because wind machines are only useful under radiative freeze conditions when a significant inversion exists. Other types of protection, such as coverings or bloom delay, must be provided during advective freezes.

During an inversion freeze, the air above the orchard is warmer than the air near the ground (Fig. 20.3c). Radiation from the surface, conduction of heat from the air near the surface to the surface and the absence of convective energy transfer result in the typical inverse-temperature curve in relation to the curve during the daytime. Inversions develop on clear, calm nights, which allow radiational and conductive-to-radiational heat losses from the surface. Inversions are responsible for fogs, valley clouds and pollutant trapping in the lowest layers of the atmosphere. The temperature stratification that develops during an inversion is difficult to modify. Significant power – approximately $1.86 \times 10^4 \text{ W s}^{-1} \text{ ha}^{-1}$ – is necessary to modify an inversion with wind machines sufficiently to provide freeze protection. Temperature modification can equal about one-quarter of the inversion-temperature difference or one-half of the temperature difference between 2 and 20 m. Once the protection has been established, the machine must keep working or the inversion will re-establish.

Wind machines should be started before the temperature approaches critical, since it is easier to maintain a temperature than to produce an increase in temperature. Inversions will not be present when naturally occurring winds mix the air, when clouds are present to reradiate energy back to the surface or when cold air can drain away from a site. Wind-machine mixing of the air above the orchard with the air in the orchard tends to equilibrate the energy in the system making orchard temperatures higher (Plate 20 6). Wind-machine air movement is proportional to the propeller r.p.m. High fan speeds are necessary for the desired temperature modifications.

Helicopters – the larger the better – are effective in mixing inversions. The pilot can monitor the inversion and operate at the optimum altitude. Thermometers that trigger small lights at temperatures slightly above the critical temperature can be placed throughout the orchard and the helicopter can move so as to extinguish the lights immediately after they turn on. Scheduling helicopters, flying at night, flying over haz-

ardous areas, flying at low altitudes and the necessity of refuelling and service stops are problematic in obtaining the desired continuous inversion mixing.

Wind machines should be located in the centre of the area to be protected or slightly to the upwind side. Fans rotate through 360° in 3–4 min. Most machines have 4 m diameter propeller blades mounted at a very slight angle at the top of 10 m towers. Single-propeller machines of about $1.86 \times 10^5 \text{ W s}^{-1}$ can protect about 4 ha, and double-propeller machines can protect about 6 ha. Machines should be serviced regularly, with tuning, fuelling, charging, lubricating and tachometer checks and mechanical checks of all moving parts and their fasteners. The energy consumption of wind machines is low relative to that of heaters. Machines need to be started before they are needed and idled until they are used. Wind machines with supplementary heaters are more economical than heaters only when additional heat is needed. Wind-machine/heater synergy ranges from 20 to 30%. One study found that the combined response of a wind machine and 20 heaters ha^{-1} is about equal to about 55 heaters ha^{-1} alone. Machines of $1.86 \times 10^5 \text{ W s}^{-1}$ on 12 m towers supplemented with about 93 heaters ha^{-1} evenly spaced throughout the area worked very well in another freeze. Of course, heater density and placement should counteract colder upwind borders and corners.

20.9.5 Bloom delay

20.9.5.1 Genetic control

Time of apple flowering is influenced by the climate and the genotype, with full bloom dates varying by as much as 6 weeks. Most cultivars, however, bloom within a 3-week period. The time of leaf-bud burst is correlated with the date of flowering and cultivars can be selected for late flowering on the basis of leaf-bud burst. Seeds of late-flowering genotypes have higher chilling requirements and germinate over a much longer period than

seeds of early-flowering genotypes. Dormancy is a complex polygenic trait. Therefore, expensive, time-consuming breeding has been limited to fruit quality and resistance to disease, with little attention to hardiness or bloom date.

20.9.5.2 Bioregulators

Bioregulators, including the plant growth hormones ethylene, auxin, gibberellin and abscisic acid, have been used to delay bloom of several species of orchard trees. While they do give some bloom delay, in general, they have too many side-effects to be useful. Oils, 1,2-dihydro-3,6-pyridazinedione (maleic hydrazide), butanedioic acid mono(2,2-dimethylhydrazide) (daminozide), 2-chloro-*N,N,N*-trimethylethanaminium chloride (chlormequat), and aminoethoxyvinylglycine (AVG) have also proved to be ineffective or contraindicated or to delay apple bloom for only a limited time.

20.9.5.3 Evaporative cooling

Evaporative cooling has been used to delay bloom of apple for as long as 17 days. The technique requires determination of the end of endodormancy and is facilitated by monitoring of anthesis phenology. Water applications to induce evaporative cooling, which are more effective in arid climates with low humidities that facilitate evaporation, should begin shortly after endodormancy ends. To initiate cooling, a thin coat of water should be applied to the tree when temperatures in the orchard are several degrees warmer than the approximate 5°C (41°F) threshold of apple-tree growth. Evaporation of the water absorbs thermal energy from the tree and the environment, resulting in mid-afternoon temperature differences of as much as 20°C (36°F) between sprinkled trees and their controls. In dry areas, evaporative cooling is more than 90% efficient in reducing fruit-bud temperatures to the wet-bulb temperature. Significant bloom delay can be obtained in these areas (Plate 20.7).

Almost all of the applied water should be allowed to evaporate to produce the cooling effect before more water is applied.

Commercial bloom-delay systems have used impact-type sprinklers, which usually deliver too much water and may cause soil waterlogging and exacerbate diseases. Water-application systems utilizing umbrella and misting nozzles, controlled by leaf-wetness gauges, have been more successful in producing delays without over-application of water, but they are more expensive. All systems require automatic water flow and draining equipment. Calcium carbonate build-up on trees in some studies did not have an adverse effect on subsequent tree growth or production.

Approximately 25% of the thermal energy required for apple flower-bud development from the end of endodormancy to full bloom is utilized to develop to bud swell, the first stage of observable phenological development. Another 25% is received by the time of the tight-cluster stage of development. When evaporative cooling for bloom delay is applied correctly within these phenological limits (end of endodormancy to tight-cluster stage), it will be successful and will avoid most of the complications – fire blight, apple scab, waterlogging, delayed root growth, fertilizer leaching and hydration of flower buds, which results in decreased hardiness – connected with water applications nearer full bloom.

It is important to apply evaporative cooling during the time when the tree is still relatively dormant and there is time for water-saturated soils to drain before root growth begins. In one study, evaporative cooling was applied for 348 h over a 40-day period to produce a 17-day bloom delay; sprinkling for a subsequent additional 238 h produced only an additional 3-day delay. Bloom delay in short-growing-season production areas produces mature apples with the same size and colour but with lower soluble solids than non-delayed fruit, but the difference in harvest time is only a fraction of the delay in bloom.

20.9.5.4 Energy reflectants

Energy reflectants can be applied to buds and limbs of trees during the winter to produce a bloom delay of several days. The tem-

Table 20.5. Use of freeze-protection methods.

Method	Freeze type		
	Advection	Radiative	Advection/Radiative
Heaters	No	Yes	No/Yes
Wind machines	No	Yes	No/Yes
Ice encasement	No	Yes	No/Yes
Under-tree sprinkling	No	Yes ^a	No/Yes ^a
Bloom delay	Yes	Yes	Yes/Yes
Site selection	Yes	Yes	Yes/Yes

^aUnder-tree sprinkling does not work in some areas.

perature of the tree remains lower than that of control trees due to reflection rather than absorption of radiant energy, so that development is slower.

20.9.5.5 Shading

Trees that are shaded during anthesis so that their temperatures are lower than ambient will bloom several days later than those growing in direct sunlight

20.9.5.6 Trunk refrigeration

Trunk refrigeration has been used to delay bloom of apple and peach trees. However, expensive refrigeration apparatus, distribution pumps, lines, insulation and specialized equipment to regulate water stress in the tree make the method costly and impractical.

20.10 Summary

Freeze-protection-method use is summarized in Table 20.5. All freeze-protection methods listed have been used successfully during radiative freezes, but only site selection and bloom delay are effective in avoiding freeze losses due to advective freezes. Protection during advective/radiative freezes depends on the severity of each component. If the advection is relatively mild, with cloud cover and humid air to moderate temperature drop, and the crop survives the advection freeze, the methods that are successful during radiative freezes may save the crop. However, if the advection is severe, crops will be lost. Therefore, selection of a freeze-free site is by far the best solution. All other solutions are more expensive and make the enterprise less profitable

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21 Integrated Fruit Production for Apples – Principles and Guidelines

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21.1 The Concept of Integrated Fruit Production (IFP)

The development of integrated production (IP) has been the result of the collaborative effort of many scientists, mainly during the last 25 years, and of two leading organizations: the West Palearctic Regional Section of the International Organization for Biological and Integrated Control of Noxious Animals and Plants (IOBC/WPRS) (<http://www.iobc-wprs.org>) and the International Society for Horticultural Science (ISHS) (<http://www.ishs.org>). IOBC/WPRS is one of six regional sections of the IOBC; it is an independent, non-profit, scientific organization established in 1956 to promote environmentally safe methods of pest (animals, pathogens and weeds) control in plant protection and, later, to promote the development and adoption of IP methods. The IP Commission of the IOBC/WPRS

(<http://www.admin.ch/sar/faw/iobc>) is responsible for developing and administering IP guidelines, while several working groups provide crop-specific technical information. The ISHS was established in 1959, with the aim of promoting and encouraging research in all branches of horticulture.

The term 'integrated production' was coined at a meeting organized by IOBC/WPRS, held at Ovrannaz, Switzerland, in 1976. As a result of this meeting, IOBC/WPRS published a document that is considered the starting-point for IP in Europe (Steiner, 1977). Since then, IOBC/WPRS has been the leading organization in promoting research on and extension of IP and has published several guidelines, both general and crop-specific, some of them in collaboration with the ISHS. The guidelines can be downloaded from the IOBC/WPRS IP Commission internet homepage mentioned above.

IOBC/WPRS has defined IP as a 'farming system that produces high-quality food and other products by using natural resources and regulating mechanisms to replace polluting inputs and to secure sustainable farming' (Boller *et al.*, 1999). Within the framework of this general definition, IFP is defined as 'the economical production of high quality fruit, giving priority to ecologically safer methods, minimizing the undesirable side effects and use of agrochemicals, to enhance the safeguards to the environment and human health' (Cross and Dickler, 1994). These definitions have been widely accepted worldwide and are part of the national regulations of several countries, such as Switzerland

Unlike organic farming, IFP does not seek to eliminate the use of agricultural chemicals but rather to reduce (or even eliminate in some cases) production inputs with high environmental impacts, such as broad-spectrum pesticides or fertilizers, and to favour safer alternatives (Sansavini, 1990, 1997; Plate 21.1)

21.2 The Principles of IP

The principles of IP, according to IOBC/WPRS, are shown in Table 21.1 (Boller *et al.*, 1999). IP represents an ecological approach to crop production and relies on ecosystem management and on the preservation of natural resources. It is a holistic concept and is not merely a combination of several elements, such as integrated pest management (IPM), together with some agronomic measures. Agrosystems are the

basis for the planning and realization of all farm activities, particularly those with potential ecological impact. They are the visible expressions of the holistic concept and provide both a natural resource and a management component. The entire farm is then the basic unit for IP implementation, as IP applied on isolated individual areas is not compatible with achieving a holistic approach. Important strategies, such as achieving balanced nutrient cycles and having an optimum allocation of farm machinery, only become meaningful if considered across the entire property. Some of the IP principles (such as the maintenance of stable agroecosystems and the support of biological diversity) should be applied on an even wider scale and, in fact, are more easily applied across large areas. For that reason, IOBC/WPRS focuses on the importance of growers' associations to implement IP programmes.

IPM is a key component of IP. Numerous case-studies have shown that the adoption of a sound IPM programme is often the first step in implementing IP practices (see, for example, Case-study 1). To avoid misunderstanding, the widely recognized definition of IPM is:

A pest management system that, in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest populations at levels below those causing economic injury

(FAO Panel of Experts on Integrated Pest Control, 1967)

Table 21.1. IP principles according to IOBC/WPRS (from Boller *et al.*, 1999)

1. IP is applied only holistically
2. The external costs and the undesirable impacts of agriculture are minimized
3. The entire farm is the unit of implementation of IP
4. The farmers' knowledge of IP must be regularly updated
5. Stable agroecosystems are to be maintained as key components of IP
6. Nutrient cycles are to be balanced and losses minimized
7. The intrinsic soil fertility is to be preserved and improved
8. Integrated pest management is the basis for decision making in crop protection
9. Biological diversity must be supported
10. The quality of the final products must be evaluated using the ecological parameters of the production system, as well as by the usual external and internal quality parameters

IP and IFP are, then, much broader concepts than IPM or integrated plant protection (IPP) and are derived from the expansion of the principles of IPM to all field practices (Sansavini, 1990). The emphasis of plant protection in the context of sustainable agriculture is placed on preventive measures ('indirect plant protection'), which must be utilized to the fullest extent before direct plant-protection measures (i.e. control measures) are applied (Boller *et al.*, 1998). Decisions about the necessity to apply control measures must rely on the most advanced tools, such as prognostic methods and scientifically verified thresholds. The application of direct plant-protection methods is only used if economically unacceptable losses cannot be prevented by indirect plant-protection methods.

Biological diversity includes diversity at the genetic, species and ecosystem level. It is the backbone of ecosystem stability, natural regulation factors and landscape quality. Replacement of pesticides by natural regulation factors cannot adequately be achieved without adequate biological diversity. The conservation and enhancement of biological diversity is therefore an important element of IP (Boller *et al.*, 1999). IOBC/WPRS IP guidelines include, as mandatory, the existence of an ecological compensation area, which must cover at least 5% of the total farm area (excluding any area of forest). The ecological compensation area includes areas with no input of fertilizers and pesticides, such as hedges, natural areas and field boundaries. Special cases might be individually owned orchards and vineyards within larger complexes of crop production. In this case, IOBC/WPRS recommends that the IP organization identifies the 5% area of the entire area owned by its members (Boller *et al.*, 1998).

The quality of products obtained under IP systems must be measured not only in terms of external and internal quality (which must be as high as under conventional production), but also in terms of impacts on the environment and on human health. Hence certification testifying to the achievements of the producer and defining the requirements that have been met during the storage,

processing and handling of products is a prerequisite for the IP label.

The principles of IPP and IP, as well as the description of the evolutionary steps from chemical control to IP, have provided important orientation marks for the development of a sustainable approach in agriculture during the last two decades (Boller *et al.*, 1998).

21.3 Integrated Production for Apples

The third edition of the IOBC/WPRS guidelines for the IP of apples was published in 2002 (Cross, 2002) and the full text is available at the IOBC/WPRS IP Commission internet site, mentioned above. The key items covered in the document and discussed below are summarized in Table 21.2

At least two ecological options for the active enhancement of biological diversity are required, such as the use of nesting boxes and/or perches for predatory birds, refuges for predators, host plants for beneficials and new wildlife habitats. The increase in biodiversity is more easily achieved in more or less permanent agroecosystems, such as apple orchards, mainly in cool climates, where a permanent green cover can be maintained all year round (Boller *et al.*, 1998).

For new orchards, site selection, rootstocks, cultivars and planting systems must be selected and harmonized so that regular yields of quality fruit, and hence economic success, can be expected with the minimum use of both agrochemicals and other environmentally hazardous practices. Chemical soil sterilization is not permitted. The cultivar chosen must offer good prospects for economic success with minimal use of agrochemicals. For example, 'Golden Delicious' must not be planted on sites prone to russetting or 'Jonagold' on sites unfavourable for fruit colouring and firmness. Cultivars resistant or tolerant to diseases and/or pests are preferred. Planting material should be of high quality and certified as being virus-free

Soil must be sampled and chemically

Table 21.2. Items covered by the IOBC/WPRS-ISHS guidelines' integrated production of apples (from Cross, 2002)

-
1. Definition of integrated production of pome fruits
 2. Professionally trained, environmentally and safety-conscious growers
 3. Conserving the orchard environment
 4. Site, rootstocks, cultivars and planting systems for new orchards
 5. Soil management and tree nutrition
 6. Alleyways and weed-free strip
 7. Irrigation
 8. Tree training and management
 9. Fruit management
 10. Integrated plant protection
 11. Efficient and safe spray-application methods
 12. Harvesting, storage and fruit quality
 13. Postharvest chemical treatments
-

analysed prior to planting. Regional or national guidelines must set out a clear method by which fertilizer requirements are determined and define both sampling and analytical procedures and the rules on which decisions are to be made. It is recommended that N-min tests be used. The N-min test determines the existing share of mineral nitrogen (nitrate and ammonium) in the soil. On the basis of humus content and soil type, the nitrogen replacement value of the tree row is estimated and, finally, the nitrogen fertilization is calculated. The maximum nitrogen input (expressed in $\text{kg ha}^{-1} \text{ year}^{-1}$) and the timing and methods of application must be defined and managed in order to minimize leaching. The same principles apply to all other major nutrients with high polluting potential.

The aims of ground-cover management are:

- to maintain plant-species diversity in the orchard, thus fostering ecological stability;
- to minimize the use of herbicides (avoiding residual chemicals completely);
- to avoid soil erosion and compaction in alleyways, without detriment to yield and with minimum inputs of fertilizers and irrigation water.

Bare-soil management over the entire orchard is not permitted. Alleyways must be of grass and/or herbs and be of adequate width to accommodate easily a vehicle passing along the rows. Non-competitive grass/herb mixtures are recommended. Regional or national guidelines must specify

a maximum width for the weed-free strip and/or percentage of the soil surface that may be weed-free.

Where possible, in established cropping orchards with excessively vigorous growth, the use of herbicides must not be permitted. To avoid undue competition for moisture and nutrients, a weed-free strip should be maintained by mulching or by covering the soil surface or through the use of mechanical cultivation. It is recommended that, where possible, ground cover is allowed to develop in the weed-free strip at times of year (such as in winter) when soil moisture is adequate. Herbicides must not be used to achieve overall bare soil and the avoidance of the use of selective broad-leaved weed herbicides in the alleyways is recommended.

Trees must be trained and pruned to achieve a manageable uniform size and a balance between growth and regular yields and to allow good penetration of light and spray chemicals to the tree centre. The use of non-naturally occurring, synthetic, plant growth regulators is not permitted. Excessive growth should be controlled by cultural measures, including the use of reduced fertilizer and irrigation supply, summer pruning and approaches to achieve greater blossom set.

Priority must be given to natural, cultural, biological, genetic and biotechnical methods of pest, disease and weed control, and the use of agrochemicals must be minimized. Plant-protection products may only be used when justified and the most selective, least

toxic, least persistent products, which are as safe as possible to humans and the environment, must be selected (Plate 21.2). Populations of key natural enemies (such as phytoseiid mites on apple or anthocorid predators on pear) must be preserved. At least two key natural enemies in each crop must be identified in national/regional guidelines. This means plant-protection products toxic to them may not be used. Where phytoseiid predators are absent from apple orchards, they should be introduced where necessary. There are some excellent books on IPM of apple pests (Beers *et al.*, 1993; Statewide Integrated Pest Management Project, University of California, 1999).

The following criteria should be taken into account in the selection of pesticides for use in IP programmes:

- toxicity to man;
- toxicity to key natural enemies;
- toxicity to other natural organisms;
- pollution of ground- and surface water;
- possibility of provoking an increase in pest populations;
- selectivity;
- persistence;
- incomplete information;
- necessity of use.

Postharvest treatment with synthetic, non-naturally occurring antioxidants for control of superficial scald and other disorders is not permitted. In order to minimize the use of fungicide sprays shortly before harvest for control of storage diseases, postharvest fungicide treatment of fruit is permitted where several conditions have been fulfilled (Cross, 2002)

21.4 IFP Implementation/Adoption

The development of IFP in Europe was closely linked to the early work on apple IPM in the 1960s (Dickler and Schaefermeyer, 1993). However, the adoption of IFP practices by growers was slow and took many years. In the 1970s, the first grower organizations, such as the Groupement des Arboriculteurs Lémaniques Pratiquant les Techniques Intégrées (GALTI) in Switzerland and the

Comité Française pour la Valorisation de la Production Fruitière Intégrée (COVAPI) in France, began to embrace IFP practices. In 1989, the Arbeitsgruppe für den integrierten Obstbau in Südtirol (AGRIOS), an IFP organization in the apple-growing area of northern Italy, published the first comprehensive IFP guidelines (see Case-study 1). Fruit grown according to the guidelines is certified and sold with a special label that identifies it as coming from IP. The publication of the AGRIOS guidelines was an important event, since it stimulated similar efforts in other European fruit-growing areas. In 1991, working groups of IOBC/WPRS and the ISHS jointly developed IP guidelines for pome fruits. The goal was to harmonize regional guidelines and set European standards for IFP. Many European fruit-growing areas have now adopted IFP programmes, which generally follow the principles set forth by the IOBC/WPRS guidelines for pome fruits. Major apple-growing countries around the world have followed the European example and have developed their own IFP programmes, including South Africa, Argentina (see Case-study 2), Brazil, Chile, Uruguay and New Zealand (see Case-study 3). Sustainable-agriculture research and education programmes similar to IFP are also under way in several fruit-growing areas in the USA, such as Oregon (see Case-study 4), but they still lack certification and marketing components.

Several reasons may explain the rapid increase in the number of IFP programmes that followed the publication of the first AGRIOS guidelines in 1989:

1. The AGRIOS programme underlined, for the first time, the economic benefits of IFP in terms of production costs, marketing opportunities and consumer safety (Dickler and Schaefermeyer, 1993). IP fruit does not generally get a higher price, but several large-scale European produce distributors prefer it to conventionally produced fruit, since the label 'from integrated production' adds value (i.e. ecological quality) in the eyes of distributors as well as consumers. Although both organic and IP fruit could meet the requirements for ecological quality, only IFP is expected to meet these objectives at the commercial level (Sansavini, 1990; Boller *et al.*, 1998).

2. The interest of consumers in a 'safe and healthful food supply' is increasing. This trend began in the 1980s and is continuing (Boller *et al.*, 1998).

3. The agricultural policy of the European Union (EU) actively promotes the adoption of IFP practices. Specific EU regulations for IP practices are still lacking at this time. However, the EU financially supports, through subsidies, grower organizations as well as individual growers who have operational programmes in place whose objectives include the 'promotion of Integrated Production or other methods which respect the environment' (EU Directive 2200/96). It is expected that the EU will eventually adopt uniform IFP standards that will apply to all member countries.

Apple acreage under IFP programmes has been steadily increasing in Europe. According to a survey conducted in 1994, 35% of the apple production area was under IFP or similar systems. This represented a 40% increase in IFP acreage since 1991 (Cross *et al.*, 1996). The same survey found a considerable drop in pesticide use in orchards under IFP programmes. A more recent survey, conducted in 1997, showed that the adoption of IFP was considerably higher in central and northern Europe (E. Dickler and E. Olivella, Spain, 1999, personal communication). For instance, in Switzerland, where more than 70% of apple production is under IFP, it has become difficult to market fruit if it does not have an IFP label. The same is true for New Zealand, where all fruit destined for export must have an approved IFP label. It is expected that IFP or similar production systems will become the standard for growing apples and other tree fruits in Europe and other fruit-growing areas.

21.5 Case-study 1: Integrated Production for Apples in South Tyrol (Italy)¹

The South Tyrol, also called Alto Adige (northern Italy) is one of the biggest pome-

fruit-growing areas in Europe. It stretches for about 110 km along the Etsch valley, which is 3 km wide on average and is flanked by high mountain ranges. The altitude varies from 300 to 1000 m above sea level. The soils are mostly light-textured, permeable, sandy loam soils with a pH of 5.5–7.0 and a fairly balanced nutrient content. The average rainfall varies from 600 to 800 mm year⁻¹. The minimum winter temperature may reach -10°C, exceptionally -15°C, and the maximum summer temperature may reach 30°C.

The fruit farms are small, with an average size of 3–4 ha. The orchards are scattered across the slopes and the floor of the Etsch river valley. At present, there are about 8000 orchard owners. The area devoted to apple production in South Tyrol is 17,600 ha. In 2001 the total pip-fruit production was 940,000 t.

The history of apple (and pear) production in South Tyrol shows the progression from conventional agriculture to IFP through IPM. The occurrence of several cases of pest resistance (European red mite in 1964 and 1982, leaf-miners in 1969 and 1988, pear psylla in 1973) led the South Tyrolean Advisory Service to implement IPM programmes (1977–1987) through the organisation and supervision of 15 grower working groups. A reduction of the number of insecticide and acaricide applications and an increase of biological control (woolly apple aphid and European red mite) were already occurring at this time.

As a result of the initiative of the institutions and organisations involved in fruit production in South Tyrol, the Working Group for Integrated Production in South Tyrol (AGRIOS) was formed in 1988. The first edition of the AGRIOS guidelines was a milestone in European IP, and it was published in 1989 under the supervision of Dr Hermann Oberhofer. At present, AGRIOS activities include the elaboration and publication of guidelines for fruit production and storage; the adjustment of the IFP programme to meet production and marketing requirements; the administration of the

¹ Source: W'erer, P., AGRIOS Workgroup for Integrated Fruit Production in South Tyrol, and W'adner, W., Sudtiroler Beratungsring für Obst und Weinbau, <http://www.agrios.it>

participating producers and packing-houses; the preparation, publication and distribution of the AGRIOS newsletter (c. 12 a year, 6500 copies per newsletter); and the control of the participating farms and packing-houses. AGRIOS guidelines follow the conceptual framework of IOBC/WPRS. They give a special emphasis to the ecological measures that have positive impacts on the orchard and the environment and to the use of biological and biotechnical pest-control measures. A list of ecological measures is given and the grower is encouraged to apply as many of them as possible each year of production. Some of the ecological options are: green cover all year round, hanging up of nesting boxes; creation of refuges for weasels, hedgehogs and other animals; introduction of phytoseiid mites, planting of hedges and bushes in the edges of the orchards; and installation of perches to attract birds of prey (falcons, owls). Due to historical pest-resistance problems, resistance management is also an important part of the guidelines.

In spite of the production and marketing pressures, the introduction and application of IP according to the AGRIOS programme met many difficulties in South Tyrol, since both growers and packing-houses had a sceptical and doubtful attitude towards a concept that established precise rules for the participants. In 1989, only 929 orchards covering 1824 ha and 44 packing-houses joined the AGRIOS programme, and therefore the IP label was not released. However, by 2001, 15,337 ha (87% of the total fruit-growing area) were initially enrolled in the IP programme and 6954 growers produced 732,920 t of integrated fruit (78% of the total South Tyrolean pome-fruit production). Grower success in the full adoption of the programme in 2001 was very high, as only 11% of the total acreage initially enrolled was voluntarily dropped by the growers or eliminated after orchard or field-book inspections.

As a result of the application of the programme, fewer residues are present in fruit,

the professionalism of the growers has increased, the image of South Tyrol production is much better and new markets have been opened.

21.6 Case-study 2: Integrated Production for Apples in Patagonia (Argentina)²

The Alto Valle del Río Negro (Upper Valley of the Negro River) is an Argentinean region whose main economic activity is fruit production. Its production of apples and pears represents about 80% of the national production and most of it is dedicated to export. The climate is temperate, continental and arid, making irrigation necessary.

The development of the IP programme for apples and pears began in 1994, with the aims of increasing and identifying the quality level of fruit produced in order to increase exports, to have access to the most exacting markets, to create a positive image of the region (in terms of human-health and environmental-protection issues) and to preserve the natural resources of the region. The programme was based on the philosophy and concepts of IOBC/WPRS and its definitions were accepted. The guidelines and the field and storage logbooks were established by a group of more than 50 persons who worked for private and public firms or were independent advisers. The guidelines include the usual sections on grower training and the options available for the management of orchard environments, sites, rootstock and cultivar selection, irrigation scheduling, soil, tree and fruit management, pest control, postharvest management and certification requirements.

Ten growers and 17 companies applied the programme for the first time in 1995/96 on 100 ha of orchards. The area officially under IP increased up to 1200 ha and then has stabilized around 700 ha since 1999/2000. However, IP is applied by a great percentage

² Source: Magdalena, C., Di Masi, S. and Colodner, A., *Programa Producción Integrada de Frutas Patagonia*, <http://www.inta.gov.ar/altovalle/proneupam.html> (information on Alto Valle); <http://www.inta.gov.ar/altovalle/ppfi.html> (information on IFP); <http://members.tripod.com/intecace/> (IFP Directives)

of growers without being certified. The IP methods used in Patagonia do not show any economic differences over conventional methods. In fact, growers have not obtained any economic advantages in the short term. However, they mention other advantages, such as the small environmental impact and the increase in biodiversity. The programme is not subsidized and it is audited by an independent body

21.7 Case-study 3: Integrated Production for Apples in New Zealand³

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New Zealand's 1500 apple growers export about 300,000 t of apples annually. Over 90% of the Class One apples are exported to more than 60 countries, mainly to the UK and Europe (50%) and the USA (25%). The New Zealand industry faces high production and transportation costs compared with its southern-hemisphere competitors and has therefore used fruit quality and new cultivars as points of differentiation to maintain orchard profitability. In the mid-1990s, food safety and environmentally sensitive production systems became important customer requirements in these key export markets. However, phytosanitary issues were also important factors that needed consideration before the New Zealand fruit industry changed from a production system that targeted international quarantine standards towards one based on IFP principles.

Implementation of the IFP programme for apples and pears in New Zealand began in 1996. A national IFP Pip-fruit Committee, led by ENZAFRUIT, which included technical experts, growers, consultants, consumers and the agrochemical industry, developed IFP guidelines based on the philosophy and concepts of the IOBC/WPRS. The committee also established technical subcommittees

and these developed chapters for the IFP manual, covering site selection, rootstocks and cultivars, soils and nutrition, water management, understorey management, tree management, spray application, pests, diseases, orchard environmental quality, industry operations, cleaner production, grower training and auditing

The IFP pest- and disease-management strategy was largely developed from earlier IPM research findings and became the initial focus for IFP implementation. Prior to the adoption of the IFP programme, the pest-control strategy was based on a regular schedule of broad-spectrum organophosphate (OP) insecticides, primarily for the control of tortricid leaf-rollers. The main goals of the new pest-control strategy were to reduce total insecticide use and eliminate OP insecticides from apple production by 2001. To achieve these goals, the programme encouraged the use of selective pest-control methods to maximize biological control and the development of postharvest pest-removal systems to decrease the risk of quarantine-inspection failures.

The introduction of IFP in apples had a dramatic impact on insecticide use nationally. Between 1996 and 2001, the total number of applications declined regionally by 42.58%, while OP insecticide use declined by 90% (azinphos-methyl use declined by 97%, chlorpyrifos use by 82% and diazinon use by 90%). Fungicide applications declined by 13%. As a consequence, biological control of some pests (woolly apple-aphid control by *Aphelinus mali*, European red-mite control by *Typhlodromus pyri* and mealybug control by general predators) has become more widely established

As for other IFP management practices, all growers must have training and certification for the safe handling of agrochemicals, and spray-application equipment must be regularly calibrated. The use of residual herbicides has decreased markedly and the weed-free strip in tree lines is now typically

³ More information: Walker, J.T.S., Marktelow, D.W.L., Wearing, C.H., Lo, P.L. and Suckling, D.M. (2001) Development of integrated fruit production programmes in the New Zealand horticultural industry *IOBC/WPRS Bulletin* 24(5), 39–44

below 30% of the orchard area. Responsible fertilizer use and irrigation management are encouraged and increasing recognition is now given to soil health and the maintenance of soil organic matter in the IFP programme.

One of the key achievements of the IFP programme has been its rapid and complete adoption by the apple industry. In the 1996/97 season, 88 growers joined a pilot IFP programme and, by 2000/01, over 90% of growers participated. IFP is now the minimum export standard for New Zealand's apple growers. IFP recommendations are reviewed annually, analysing industry-wide pest monitoring and control records, together with fruit-quality data obtained from packing-house grading procedures. This allowed identification of difficulties and provided the basis for programme revisions to ensure that fruit quality and growers' confidence in the programme was retained throughout. During implementation, growers were also required to attend discussion groups led by trained facilitators. Any issues arising from these groups were collated nationally and resolved by scientific experts, who then informed all facilitators.

Several factors contributed towards the rapid implementation of IFP. One of the most important was having a unified marketing structure, where one organization could set uniform production standards across the whole industry. ENZAFRUIT also assisted implementation by giving a small financial incentive to IFP growers. But most growers welcomed the move away from intensive use of OP insecticides and found that the IFP programme did not incur significant additional costs, while the fruit quality at harvest was comparable with the old OP-based programme. At present, growers enjoy the IFP programme and they have clear marketing benefits with customers. The grower-owned company New Zealand Pipfruit Limited now manages the programme. An independent agency, on behalf of exporting companies, audits growers' pesticide use and compliance with the programme, to ensure the integrity of IFP.

21.8 Case-study 4: Integrated Production for Apples in Northern Oregon (USA)

For the last 10 years federal funding initiatives under the Sustainable Agriculture Research and Education (SARE) grants programme have promoted the adoption of sustainable agricultural production practices in the USA (<http://wsare.usu.edu/>). Similar to IP, the mission of SARE is to expand the adoption of sustainable agricultural practices that are economically viable, environmentally sound and socially acceptable. This considerable investment in sustainable agriculture has spawned a number of producer organizations in the USA with their own guidelines and eco-labels. However, compared with other fruit-growing regions around the world, especially Europe, efforts to establish IP programmes for apples and other tree fruits with recognized labels and full certification programmes have so far been limited. Often these programmes involve producers in a limited geographical area and are not inclusive of all production practices. Their focus has generally been on IPM and restricting the use of agricultural chemicals, especially broad-spectrum pesticides. Examples are the 'Core Values Northeast' programme (<http://www.corevalues.org/>) for apples in the north-eastern USA and the 'California Clean Growers' programme (<http://www.californiaclean.com/>) for fruits and vegetables.

One area that has begun to follow the European IP model is the Mid-Columbia fruit-growing district in northern Oregon. This region produces apples on 610 ha, pears on 4860 ha and sweet cherries on 2830 ha. Since the early 1990s, efforts have been under way to develop IP programmes for apples, pears and sweet cherries in that area. The IOBC guidelines for pome fruits (Cross and Dickler, 1994) served as a template for these programmes. Another IFP programme in Oregon involves grapes and is known under the acronym LIVE (Low Input Viticulture and Enology). The grape IFP programme (<http://liveinc.org/index.htm>) was developed independently of the other IFP programmes in Oregon and is the first IFP programme in the USA endorsed by the

IOBC. The pome-fruit and the cherry IFP programmes in northern Oregon are at a similar point of development. Initially, the emphasis was on building the infrastructure for each programme. This included constituting grower-led IFP committees, which oversee the development, implementation and direction of each programme. University research and extension play only a supportive role by conducting IFP-related research and grower education. IFP guidelines for pome fruits and cherries were first published in 1994 and they spell out the aims and preferred practices under IFP (<http://www.orst.edu/dept/hort/orchardnet/ifp.htm>). The IFP guidelines are annually updated. Pesticides are listed in order of preference and IFP compatibility. In addition, demonstration orchards throughout the district serve as vehicles for showcasing and promoting IFP practices such as selective pest management without broad-spectrum pesticides; biological control of major fruit pests, pest and disease control based on monitoring and model forecasts; yield mapping; and site-specific water and nutrient management. Educational programmes and materials are delivered to growers, consultants and packing-house representatives through a cooperative effort of local grower organizations and the university. The focus of educational programmes is to support knowledge-based orchard-management decision-making. To assist growers with irrigation scheduling and pest and harvest management, weather information and pest and disease forecasts are available via telephone and the Internet. This information is updated daily from a network of remote weather stations. A computerized spray-record system is being put in place for growers to report pesticide use on individual blocks. The system will track pesticide use in the district and document the implementation of IFP practices.

So far the emphasis of the Oregon IFP programmes for pome fruits and cherries has

been on education and programme development and less on marketing. No mechanism is in place at the present time to certify or audit growers. However, fruit growers who want to be certified according to production standards similar to the IFP guidelines can obtain certification through The Food Alliance (TFA), a non-profit organization dedicated to sustainable agricultural practices (<http://www.thefoodalliance.org/>). TFA guidelines emphasize three areas: pest management, soil and water conservation and farm labour. In addition to certification, TFA assists with promotion and marketing. It is estimated that about 8% of the pome-fruit and cherry acreage in the Mid-Columbia fruit-growing district is now certified by the TFA.

In addition to raising grower know-how of fruit production by updating them regularly about new technologies, the IFP programmes in the Mid-Columbia fruit-growing district have had a positive impact on horticultural and pest-management practices. This is also evident from the substantial decrease of OP insecticide use between 1993 and 1999. For instance, azinphosmethyl use on pome fruits has decreased by more than 20% over that time period. With increasing use of mating disruption and insect-growth regulators for codling-moth control, even more dramatic reductions in OP use can be expected in the next few years.

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22 Organic Apple Production – with Emphasis on European Experiences

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22.1 Introduction

Regardless of the production methods employed, fruit growing requires a large amount of care. During the long vegetation period, the trees are exposed to many pests and diseases and, since fruit trees are permanent crops, any management mistakes can continue to have an effect for a number of years. Furthermore, the demands on quality are very high, since fruit is usually sold without any processing.

Compared with the conventional producer, the organic fruit producer faces extra challenges and production risks as a result of the rigorous restrictions imposed upon production aids. Over the past years it has been possible to greatly improve yield stability in organic fruit production as a result of the substantial progress made in terms of cultivars, production aids and machinery. Additionally there have been welcome developments in the economic environment, owing to lively demand and fair producer prices.

Both the supply of and demand for organic fruit have grown rapidly since the mid-1990s. Demand continues to outstrip supply, which shows that consumers increasingly value foods that are untreated and free of pesticide residues. The fact that some of

the major wholesalers have introduced organic fruit into their range – e.g. COOP in Switzerland with their NaturaPlan range, Bila in Austria and Reve in Germany – has given the market a strong new impetus. The current market share of organic fruit is approximately 3–5% of the dessert-fruit market in Switzerland, while in Germany it is currently less than 1%. Experts agree that, in the medium term, organic fruit can increase its market share to 10% (Schmid *et al.*, 1995).

22.2 Basic Principles of Organic Farming

The aims and objectives of organic cultivation – applicable worldwide – are as follows

- to produce high-quality foods that are free of artificial and health-damaging pesticide residues;
- to build and maintain high soil fertility;
- to maintain natural cycles and processes that are as closed as is feasible;
- to promote and conserve biodiversity;
- to keep, feed and breed livestock in a manner that observes particular ethical principles;
- to work without the use of synthetic aids and ingredients, or genetically modified organisms and their derivatives.



Fig. 22.1. Rudolf Steiner (1861–1925), the founder of biodynamic agriculture

There are two main organic farming systems: organic farming and biodynamic farming, the latter essentially amounting to the former but including additional requirements and treatments. The foundations for biodynamic farming were laid with a course of eight highly regarded lectures by the scientist, philosopher and founder of the spiritual science of anthroposophy, Rudolf Steiner (1861–1925) (Fig. 22.1; Steiner, 1924). Based on this school of thought, biodynamic farming, building upon scientific principles, aims to work with non-physical forces, such as special compost preparations, which are based on minute doses, or the timing of planting and cultivation on the basis of planetary constellations (Koepf, 1993).

In the German-speaking parts of Europe, organic farming (*biologisch-organischer Landbau*) was influenced strongly in the postwar period by Dr Hans Müller and Dr Hans-Peter Rusch. Other pioneers, such as Sir Albert Howard and Lady Eve Balfour (Willer, 1995) in England, as well as Jean Boucher and Raoul Lemaire in France, enriched the movement with their work (Siebeneicher, 1995). Organic farming is based solely on science, while pursuing the same aims as biodynamics. The general guidelines formulated by Müller and Rusch

(Simon, 1995) still give shape to the organic standards used today.

The majority of organic fruit producers in Europe produce to 'organic' standards, rather than 'biodynamic' standards. Vogt (2000) provides an up-to-date historical overview and a listing of original sources.

Most of the principles and methods described in this chapter apply to both biodynamic and organic farming. We have refrained from providing a detailed description of the specific requirements and treatments used in biodynamic fruit production (biodynamic preparations, consideration of planetary constellations, composting methods, etc.) in this chapter, as this would require a more in-depth discussion of the underlying philosophy.

22.3 The Legal Basis

The legal minimum standards for organic production, processing and specification of organic products are laid down in EU Regulation 2092/91 (EEC, 2000). This regulation also forms the basis for the national organic regulations in the individual European countries and for the organic labels established under private schemes, such as Demeter, Bioland, Naturland or BIO-SUISSE (BIO-SUISSE, 1999). The private inspection and certification bodies are free to prescribe standards that are stricter than those contained in the EU Regulation. However, they must not certify to a lower standard than that set by the EU or by national legislation. Most European organic producers are members of a private inspection and certification body, because this has clear advantages in terms of marketing and access to information. A detailed comparison of the most important European sets of organic standards has been published by Häseli (1996).

To foster global harmonization of standards with the aim of achieving equivalence for organic products, the International Federation of Organic Agricultural Movements (IFOAM), an association of national organic certifying bodies under private law, established its own basic standards in 1980.

The IFOAM Basic Standards (IFOAM, 1998), which are revised every 2 years, are particularly important for countries that do not as yet have their own organic standards. They also form the basis from which the IFOAM Accreditation Programme operates – a private programme, set up in 1996, which evaluates and accredits private national certification programmes. At the public level, two United Nations (UN) organizations – the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) – adopted standards for plant products from organic agriculture in 1999 for the first time as part of the *Codex Alimentarius* (an international foods standards programme) (FAO/WHO, 1999). The standards of the *Codex Alimentarius* are important for the World Trade Organization (WTO) in assessing the equivalence of organic products. IFOAM holds observer status with the *Codex Alimentarius* Commission.

The inspection and certification of holdings is carried out in individual countries at least once a year by an independent, accredited inspection company. Certifications for imports of products into the European Union (EU) are mostly based on the certificates of the accredited certification bodies in the originating countries, provided these are recognized by the EU. Otherwise certification is carried out by accredited inspection and certification bodies within the EU.

22.3.1 Important requirements in organic fruit production

The various sets of standards mentioned above contain separate sections dealing with the rules for organic fruit production. Apart from the general production standards, the following prescriptions and recommendations are of particular importance for organic fruit producers (Table 22.1).

22.4 The Extent and Importance of Organic Fruit Production in Europe

According to a survey carried out by Haseli (1998), organic fruit production amounts to

about 2.4% of national dessert-fruit production in several of the main European fruit-producing countries. While organic fruit must still be termed a niche product, figures for relative annual growth are substantial, at between 10 and 30%. With the market entry of major wholesalers since the mid-1990s and consistently attractive producer prices, the area under organic fruit has increased in many countries. Southern Tyrol (Italy), for example, has experienced a major increase. There are numerous biodynamic fruit growers in Germany, Southern Tyrol and France, while there are only a small number of biodynamic holdings in Austria and Switzerland. Throughout Europe, almost all of organic fruit production is on holdings that have been converted in their entirety, with very few exceptions.

22.5 Supply Situation and Market Outlook

22.5.1 Outlook for the organic fruit market

In an extensive survey among experts in Switzerland in 1994, survey participants estimated the market potential for organic fruit in 2000 at approximately 10% (Schmid *et al.*, 1995), with about one-third of production reaching consumers via wholesalers.

Today the 10% market share forecast still appears realistic for the future. Its realization has been delayed because the development of these markets requires more effort on the part of traders and producers than originally anticipated.

The main obstacles are that it is essential for organic fruit to be positioned separately from conventional fruit in retail outlets, and that additional consumer information has to be provided (see Section 22.12). In order to win over the supermarket customer as a buyer of organic fruit, both the inner quality and the appearance of the fruit have to be at consistently high levels. Furthermore, the price differential to conventional fruit must not exceed certain thresholds and it must be based on transparent economic data recorded at every step in the production process.

Table 22.1. General production requirements for organic fruit growing

Topic	Recommendations	Prescriptions
Conversion		Most private certification bodies require the immediate conversion of the entire farm to organic farming practices (extension of the conversion period to a maximum of 5 years is possible). Under certain circumstances, the EU allows for partial conversion and organic production in partial separate units for an unlimited period
Soil management	Preferably permanent ground cover; species-rich flora and fauna; competing vegetation is controlled while simultaneously protecting the soil and maintaining a long-lasting natural ground cover; encourage and maintain good soil structure and soil biological activity	No herbicides; no clean cultivation
Fertilizers and mulch	Leave organic material as mulch or incorporate by shallow cultivation Prudent use of fertilizers in keeping with requirements, in order to reduce plant protection problems and to improve fruit quality	No synthetic nitrogen or phosphorus fertilizers and no muriate of potash fertilizers The use of certain bought-in fertilizers (basic slag, crude potassium salts and magnesium potassium sulphate), as well as trace elements and calcium chloride for bitter pit, require that the need be recognized by the inspection authority or inspection body and must be notified. Fast-acting calcium fertilizers, such as slaked lime ($\text{Ca}(\text{OH})_2$) or quicklime (CaO), are not permitted because of their caustic effect on soil organisms
Production systems, tree shape	Provide for sufficient light penetration and air circulation	
Cultivars, planting stock	Choose cultivars and rootstocks adapted to location and production system	No genetically modified cultivars or rootstocks; planting stock must be organically produced (transition period in the EU until 31 December 2000). A number of producer associations have developed relevant guidelines regulating the details. In 1999 the Swiss working group of organic tree nurseries (Arbeitsgemeinschaft ökologische Baumschulen (AGÖB)) published, together with the certifying bodies, a detailed compilation of quality requirements for organic planting stock. These are as strict as those for conventional stock (AGÖB, 1999)

Continued

Table 22.1. *Continued.*

Topic	Recommendations	Prescriptions
Pruning	Prune trees to 'naturally spreading' shape and moderate growth; support physiological balance in trees; remove any diseased, dead and broken limbs that harbour pests or diseases	
Plant protection	Use preventive measures to regulate pests and diseases, for example: use cultivars that are disease-resistant and pest-tolerant and that are adapted to the local soils and climate Provide habitats for beneficial insects and birds, such as strips sown in wild flowers and herbs, hedgerows, etc.	No use of synthetic plant-protection products; use of plant protectants on the basis of standardized counts; permitted aids are listed in Annex III of EU Regulation 2092/91; Switzerland has a binding limiting list showing the available products that have been tested – including the additives – for suitability with organic standards and their efficacy under organic conditions
Growth regulation and fruit thinning	Undertake timely thinning of fruit, either manually or mechanically (e.g. with the <i>Fadengerät</i> – a mechanical tool for thinning blossoms, described below)	Thinning sprays and growth regulators are not permitted
Quality and grading	Strive for the best possible inner quality and food safety	These aspects are not covered by EU regulations and usually the conventional grading rules are applied. In Switzerland, more tolerant grading rules in relation to blemished fruit and fruit sizes are applied in cooperation with the wholesale and retail trade
Storage, processing	Apply careful processing with minimum treatment Some private certification bodies do not permit juices made from concentrated fruit juice	No restrictions on atmosphere control in storage rooms There are restrictions on processing aids. Permitted aids are: agar and pectin for jams, fresh egg-white and natural casein for fining, pure-culture yeast, sulphurous acid for cleaning by fumigation, gelatin

22.5.2 Distribution channels and marketing structures

In Southern Tyrol, practically the entire organic fruit harvest is marketed through wholesalers. The main markets are Germany (70%), central and southern Italy (15%) and Great Britain (10%) (Haseli, 1998). In Germany, Austria and Switzerland, there is a similar trend towards marketing through the wholesale trade (Table 22.2).

22.5.3 Grading rules

In the EU, generally the same quality standards apply to organic and conventional fruit. In practice, organic apple producers are able to sell class II grades mixed with class I grades as dessert fruit. Switzerland is developing its own, nationally applicable rules on sizing for organic fruit. The standards are part of the *BIO-SUISSE Standards*. They are discussed on an annual basis between organic

Table 22.2. Approximate distribution (%) of organic fruit outlets among different markets (from Häseli, 1998).

Country	Wholesalers	Retailers	Direct marketing
Italy (Southern Tyrol)	95	Of little relevance	Of little relevance
Germany	60–65	25	5–10
Austria	70	20	10
Switzerland	60	25	15

fruit producers and traders and revised if necessary. The ultimate aim of these grading rules is to guarantee attractive-looking fruit with good flavour and high hygienic quality. Small blemishes are accepted by both traders and consumers, which ensures that the intensity of plant-protection measures is kept at an environmentally acceptable level and is not dictated by 'cosmetic' quality demands.

22.5.4 Producer prices

Since demand for organic fruit continues to outstrip supply by a considerable margin and higher production costs are demonstrable (see Section 22.19), organic apples achieve considerably higher producer returns than conventional ones. According to a study carried out by the Swiss Research Institute of Organic Agriculture (Forschungsinstitut für biologischen Landbau (FiBL)) (Häseli, 1998), organic producer returns in Southern Tyrol, Austria and Germany are two to three times those for conventional produce. In Switzerland, the average producer returns for organic apples in the past 2 years have been twice those for conventional ones. Retail prices for organic fruit in supermarket chains are generally between 20 and 60% higher than prices for conventional fruit. As with the grading rules, the recommended retail prices for organic fruit are negotiated between producers and traders at the start of a sales campaign and are published. A pricing scale is set on the basis of cultivar, quality grade, size class and storage duration.

22.6 Conditions Favouring the Conversion to Organic Apple Production

A conversion from conventional or integrated to organic fruit production that is to

be successful both economically and from the point of view of crop husbandry requires first and foremost highly motivated and highly skilled managers and staff. It is of benefit if the manager's family is prepared to take some risks, does not shy away from the professional challenge and enjoys living and working with a species-rich ecosystem and its many interdependencies. Continuous further education and training are very important.

It is advantageous if the orchard property has the following characteristics:

- Fruit crops, cultivars and production systems are suited to organic production and to the marketing channels envisaged, land is available for ecological compensation and the restructuring of the holding for organic production is economically feasible (for example, plant-protection measures and soil management are very difficult with high-density plantings).
- Buildings, machinery and workforce are appropriate or else the required adjustments can be financed.
- It is possible to restructure marketing channels, where necessary.
- The additional labour requirements in fruit production (for example, for manual thinning of flowers, mechanical soil cultivation, etc.) fit in well with the other farm enterprises including the times of peak labour demand.

22.7 Site Requirements

Generally the minimum requirements used for site selection for organic fruit production are slightly higher than those for conventional production. The limited or, in some cases, non-existent possibilities for direct plant-protection measures (e.g. for scab

(*Venturia maequalis* (Cke.) Wint.), powdery mildew (*Podosphaera leucotricha* (Ell. & Ev.) Salm.), sooty blotch (*Gloeodes pomigena* (Schw.) Colby), apple-blossom weevil (*Anthonomus pomorum* L.), voles and mice) means that optimum site conditions are essential, including the following:

- **Location.** Sites in high-rainfall areas with precipitation of more than c. 1300 mm per annum are less suitable for organic production because of the restricted options for plant protection. The proximity of woodlands can lead to additional insect problems (apple-blossom weevil, bark beetles (*Xyleborus* = *Anisandrus dispar* F.)) or can impede the drying off of foliage.
- **Exposure.** Sunny, good air flow (to minimize the incidence of fungal diseases), slightly sloping ground (to allow hoeing or mulching of tree rows), as frost-proof as possible.
- **Soil.** Must be of at least medium depth; good structure and well-drained (for good trafficability); good humus content to promote high biological activity and sufficiently quick mobilization of nutrients in the spring, well-balanced soil fertility (to compensate for the limited possibilities for foliar feeding or the application of synthetic fertilizers).

22.8 Planting Systems

The chosen planting system should aim to combine cultivar, rootstock and planting density in a manner that results in 'moderately' growing, productive trees. It is crucial that the system is adapted to the options available for mechanization and labour deployment on the property.

In many organic orchards, dessert apples are harvested from trees on seedling rootstocks. These are mostly old or local cultivars, which are used for self-sufficiency and direct marketing. It is well known that the profitability of standard trees (i.e. those on seedling rootstock) for dessert-quality fruit is well below that of trees on dwarfing rootstocks. However, standard trees are strongly image-building and are highly valued by a

part of the customer base (for recommendations on production and cultivars, see FiBL leaflets on commercial organic fruit production with standard trees (Brunner *et al.*, 2000; Háseli *et al.*, 2000)). Unfortunately, the accident statistics show that not enough attention is given to accident prevention in standard-tree orchards.

The bulk of organic dessert fruit is produced on dwarfing trees. The planting densities in modern organic dessert-fruit orchards are generally between 2000 and 3000 trees ha⁻¹. High-density plantings with more than 4000 trees ha⁻¹ have been shown to be problematic for organic systems in terms of plant protection and orchard-floor management. Training regimes aim for good air flow both through the tree interior and between rows, as well as for unhindered sunlight penetration around fruit on lower limbs and near the trunk. This can be achieved, for example, with a shape that on all sides tapers strongly towards the top. Otherwise fruit on lower branches and in the centre of the tree are much more prone to disease, particularly apple scab and sooty blotch.

For organic apple production, mostly single-row spindle-bush plantations are planted. In order to make manual thinning and the training of the trees easier and also to allow for hail-protection netting, many organic orchardists limit the height of the trees to between 2 and 2.5 m. The height at which the lowest fruiting branches are trained is preferably chosen to be slightly higher than in integrated production in order to leave sufficient room for mechanical hoeing and for mulch spreaders. Using planting stock with high grafts is of benefit in order that the accumulation of soil around the trunk, which can arise from hoeing or mulching, does not lead to self-rooting of the scion cultivar. It is recommended that the ideal organic planting stock, with a high graft and a good heading height, is secured by way of a contract with a tree nursery prior to the grafting season.

Producers who use the rope machine for fruit thinning – a mechanical tool destroying a part of the blossoms by vertically rotating nylon ropes (see Section 22.15) – must try to train preferably short side-branches on

a horizontal plane. Multiple-row plantings cannot be managed efficiently because of problems in orchard-floor management, plant protection and mechanical thinning. If a rope machine is to be used, V-shaped orchard systems are also not feasible.

22.8.1 Environmental considerations in choosing construction materials

The use of modern cropping systems results in considerable material requirements for stakes, trellises, hail protection and irrigation. This is also true for organic production. There are a number of possibilities for optimizing the use of such materials from an environmental point of view, along with meeting the requirements of organic production. Instead of using treated wooden posts, trellis from tropical tree species, posts or galvanized-metal rods or native hardwoods (such as false locust, oak or sweet chestnut) could be used. Experience at the FiBL and in commercial orchards have shown that these hardwoods can also be used for supporting the hail-protection covers, which require a lot of material. A degree of environmental optimization is also possible and desirable through adopting practices that minimize the use of metal and plastic components. However, substantial progress in this regard will only be possible when well-anchored, drought-resistant rootstocks become available, as these would require neither stakes nor irrigation systems.

22.9 Choice of Rootstock

In organic fruit production, it is important to consider the selection of a rootstock in great detail in order to ensure that the rootstock is well adapted to the site (heavy or light soils, shallow or deep soils, wet or dry climate, ability to irrigate, replanting on the same ground or virgin ground, etc.). Generally organic producers use the same or a slightly more vigorous rootstock than is used in conventional orchards. Unsuitable combinations of rootstock and cultivar can easily result in too vigorous growth, a biennial-bearing

habit or too much of a dwarfing effect, each resulting in unproductive trees. The advantages and disadvantages of a number of rootstocks are described in detail in Chapter 5. Note that, during their establishment years, the more vigorous rootstocks are not much more tolerant of competition than, for example, the M.9 types. Accordingly, the use of a vigorous rootstock in organic production cannot compensate for the cost and labour-intensive control of ground-cover vegetation during the first 3–4 years after planting (see Section 22.13). When full cropping capacity has been reached, the slightly more vigorous rootstocks, such as M.26, M.4, M.7 or MM.106, are more suited to year-round ground cover in both rows and aisles than the very dwarfing, such as M.9, and extremely dwarfing types.

For the grower, the plethora of new rootstocks with little-known characteristics produced by the many breeding stations is difficult to come to terms with. Breeders are paying more attention to disease and pest resistance (e.g. to fire blight (*Erwinia amylovora* (Burr) Winslow *et al.*) or woolly apple aphid (*Eriosoma lanigerum* Hausm.), which can only be welcomed by organic producers. However, trials using new rootstocks in wholly organic orchards (in respect of plant protection, nutrient management, weed control by hoeing and some competition from weeds) are still in their very early stages (Weibel, 2000). Besides improved nutrient-uptake abilities and tolerance of weed competition, sufficient anchorage without staking is important from the point of view of the organic fruit grower.

22.10 Areas and Features for Ecological Compensation

An inherent part of a plan for an organic orchard is the integration of areas for ecological compensation to maintain and support biodiversity. Strips sown in wild flowers and herbs contribute considerably to encouraging beneficial insects and thus to reducing aphid pest species, such as the rosy apple aphid (Wyss, 1997). In order to control aphids effectively, Wyss suggests that 5–10%

of the area be sown in wild flowers and herbs. Other features of importance for beneficial insects and birds are species-rich hedgerows, consisting of native species (excluding fire blight hosts), ruderal areas established with pioneer plants, extensively used meadow strips at the fringe of the orchard, small stacks of branches and heaps of stones, nesting blocks for wild bees, perches for birds of prey, nesting boxes for a variety of bird species and so on (Plate 22.1).

The knowledge required to establish and maintain hedgerows and wild-flower strips in an optimum manner is not to be underestimated. For further reading, including practical management advice, see LBL (1993, 1994a,b,c) and Schmid *et al.* (2000).

22.11 Choice of Cultivars

The choice of suitable cultivars is of central importance to successful organic fruit production. Because of the limited options for plant protection, organic fruit production places particularly high demands on disease and pest tolerance or resistance. Additionally, management aspects must be considered, such as marketing options, available sites and the desired farm structure.

22.11.1 Choosing a suitable range of cultivars for commercial organic fruit production and marketing

22.11.1.1 *Selecting a range of cultivars that match marketing opportunities*

Marketing has a direct influence on the choice of cultivars for production. Once a marketing strategy has been decided upon, it must be adhered to consistently, at least for the lifetime of one generation of trees (*c.* 15 years), in order to ensure economic success.

Apart from personal preferences and labour availability, it is primarily the location of the orchard, i.e. the distance to customers and traders, that determines whether the fruit will be sold to wholesalers or marketed directly to the consumer. On-farm marketing can be made much more attractive with a

versatile range of cultivars rich in specialities, from summer cultivars through to late keepers. For larger and more specialized orchards, it is of interest to produce a smaller range of cultivars that are adapted to the needs of the wholesale market, thereby substantially reducing the workload involved in planning, orchard care and harvesting.

A marketing plan that is tailored to the situation in the orchard will make it clear which cultivars will be suitable and what their characteristics will have to be.

22.11.1.2 *Preferred disease-resistant cultivars for organic fruit production*

All the apple cultivars commercially available today are more or less susceptible to scab and require time-consuming, costly plant-protection measures, which, nevertheless, cannot guarantee sufficiently stable yields from susceptible cultivars. The required intensive scab-control measures are a constant headache for fruit growers. The repeated treatments are problematic environmentally (because of soil compaction, energy use and stress imposed on beneficial species of fauna) and in regard to consumer acceptance. Therefore, except in the most favourable of locations, cultivars that are moderately to highly susceptible to scab should not be used in new organic plantings. Table 22.3 shows the scab resistance of a number of commonly grown apple cultivars. An interim evaluation of the most important cropping and fruit properties of new resistant cultivars under organic management based on trials conducted by FiBL, including initial cropping and marketing experience, is evaluated in Table 22.4.

In most of today's resistant cultivars, scab resistance is based upon the single gene, *Vf*. The weakness of this approach has been demonstrated clearly by occasional resistance breakdowns. In coming years, breeders will therefore increasingly offer cultivars with multiple disease resistance. Hence, from the outset, an organic orchard should maintain options for flexible adaptation of the range of cultivars it produces.

Apart from its degree of pest and disease resistance and its taste qualities, a cultivar's

Table 22.3. Susceptibility of apple cultivars to scab (from Häseli and Bosshard, 1993, and surveys of 17 organic fruit producers 1989 to 1992).

Susceptibility to scab	Cultivars
Resistant	Various (see Table 22.4)
Low	'Glockenapfel', 'Boskoop', 'Jonathan', 'Cox's Orange Pippin', 'Delbard Jubilé'
Low to moderate	'Spartan', 'Sauergrauech', 'Berlepsch', 'Alkmene'
Moderate	'Kidd's Orange Red', 'Elstar', 'Empire', 'Gravenstein', 'Maigold', 'Idared', 'Summerred', 'Primerouge', 'Pinova' ^a
Moderate to high	'Jonagold', 'Gloster', 'Champagner Reinette', 'Jakob Lebel', 'Delbard Estival'
High	'Golden Delicious', 'Gala', 'Meran', 'Rubinette', 'McIntosh', 'Vista Bella', 'Goro', 'Ariet', 'Braeburn', ^a 'Fuji', ^a 'Delblush' ^a

^a Supplemented with more recent experience.

Table 22.4. Summary of 1998/99 interim evaluation of a number of disease-resistant apple cultivars for commercial organic production on the basis of trials and interlaboratory tests, as well as commercial grower trials, under organic conditions in Switzerland.^a

Archetype (AT)	Good impression so far	Continue observation	Less promising
'Golden' AT	'Resista' (+ flavour, + appearance, – vigorous growth with poor branching, – powdery mildew, – susceptible to rusts)	'Goldstar' (+ flavour, – prone to bitter pit, – large fruit) 'Delbard Jubilé' (+ inner quality, – large, spreading tree, – field resistance to scab only, – biennial bearer) Newcomers: 'Goldrush', 'Biogolden', 'South Tyrolean Golden' types	'Sir Prize' (+ good for processing, + yields, + little tendency towards biennial bearing and not very prone to browning of the cut surface of the fruit)
'Jonagold' AT	'Rubinola' (+ flavour, + appearance, + early harvest, + self-thinning (too) well, – yield, – strong growth)	'Angold' (+ growth habit, + flavour, + Venturia Antonovka (VA) resistance, – powdery mildew, – large fruit) 'Viktoria' (+ fruit quality (sweet type), + dwarfing tree, ? keeping qualities, ? too dark) 'Regine' (+ fruit quality, + good keeper, + tolerant of sooty blotch, – poor branching, – yield, – tough skin, – skin spots) Newcomer: CQR-10-T-17	'Delorina' (+ sweetness, + good keeper, + tolerant of rosy apple aphid, – many skin spots, – prone to powdery mildew)
'Idared' AT	'Ariwa' (+ fruit quality, + growth habit, + tolerant of powdery mildew and aphids, – fruit thinning required for fruit size and flavour)	'Florina' (+ tolerant of rosy apple aphid, + yield, + known in the market-place, – growth vigorous and difficult, – powdery mildew, – moderate eating quality)	'Saturn' (+ appearance, + growth habit, + frost tolerance, – keeping qualities, – flavour, – biennial bearer, – premature fruit fall) 'Priam', 'Liberty', 'Prima' (→ below average quality)

Continued

Table 22.4. *Continued.*

Archetype (AT)	Good impress on so far	Continue observation	Less promising
	'Rajka' (+ growth habit, + yield, +/- flavour, ? keeping qualities, ? too dark)	Newcomers: 'Lotos', 'Vesna', 'Melodie', 'Ahra', 'Ahrsta', FAW 8027	'Rosana' (+ overall, - keeping qualities) 'Reanda' (+ fire blight, - flavour) 'Nabella' (- strong growth, - susceptible to scab)
'Cox' AT	'Topaz' (+ flavour and eating quality, + relatively well known and accepted in the marketplace, - greasy, - bitter pit, - susceptible to aphids) 'Resi' (+ growth habit, + flavour, + appearance, - small fruit, - thinning required, - stores only up to 3°C)	'Renora' (+ resistant to fire blight, + dwarfing growth, - inner quality not consistent) Newcomers: 'Ecolette', 'Santana', 'Gerlinde'	
'Gravenstein' AT	'Retina' (+ growth habit, + appearance, + flavour, - keeping qualities, - susceptible to aphids)	'Julia' (+ summer cultivar, + flavour, + vigorous growth) 'Reglindis' (+ growth habit, + flavour, - bruises very easily) 'Hana' (little experience, - bitter pit) 'Nela' (little experience) 'Baujade' (+ quality, - looks like 'Granny Smith' but doesn't taste as good, - ripens very late)	
'Boskoop' AT	'Otava' (+ growth habit, + yield, + multiple disease resistance, + appearance, - sooty blotch, ? too acidic for an apple similar in appearance to 'Golden' AT)	'Rewena' (+ fire blight, + yield, - poor branching, - sooty blotch, - appearance, - flesh sometimes too soft)	'Relinda' (- strong growth, - flavour) 'Zuzana' (- strong, difficult growth, - poor disease resistance)

^a + = strength, - = weakness, ? = to be determined (as of 1999)

tendency towards biennial bearing plays an important role in determining economic success. In order to be able to cope with the high workload required for thinning in the limited time around the flowering period, the proportion of biennial-bearing cultivars in the orchard should to be kept to a minimum. 'Organic cultivars' with a strong tendency towards biennial bearing include 'Boskoop', 'Elstar', 'Maigold', 'Gravenstein'

and others. The bearing habits of new resistant cultivars are not currently known.

22.12 Organic Apple Production Requires New and Autonomous Marketing Concepts

Despite the undisputed advantages of disease-resistant cultivars for organic apple

production, producers are faced with the problem that both retailers and consumers have limited knowledge of their eating, cooking and keeping qualities, not to mention the ecological advantages of these cultivars. Additionally, the trend in the apple market towards globalization, with a limited number of globally traded cultivars, strongly counteracts efforts to introduce additional cultivars in generally small quantities. Currently available disease-resistant cultivars are very short-lived, as new cultivars with improved eating, cooking and production characteristics are constantly being bred and put on the market. In order to utilize the advantages of disease-resistant cultivars, despite the difficult conditions prevailing in the market-place, new marketing concepts have to be devised for them.

22.12.1 Grouping apple cultivars into archetypes

The extensive and short-lived range of cultivars on offer provides a complexity that both producers and the market are seeking to resolve. One way of consolidating and thus simplifying this complexity is to sort the cultivars into a few, defined groups (Table 22.5); at the retail level the groups are 'archetypes', which are then further simplified as 'flavour groups' at the consumer level (Weibel, 1995a, Weibel and Grab, 2000). The definition of the archetypes is based on the flavour and appearance of well-known commercially important cultivars. For example, the 'Golden archetype' combines all yellow, large, smooth-skinned, mild- to sweet-tasting cultivars. There are borderline cases in this classification and they may have to be revised in step with experience. Grouping into flavour groups then combines the archetypes 'Golden', 'Jonagold' and 'Idared' in the flavour group 'mild to sweet'. The 'Cox archetype' and 'Gravenstein archetype' are described as 'spicy, slightly acidic' and finally the cultivars in the 'Boskoop archetype' are grouped as 'predominantly acidic, spicy'. The cultivar name is, of course, stated at each level but the information on flavour becomes predominant.

The grouping of cultivars into archetypes gives the producer the necessary freedom to

be flexible in choosing a suitable range of cultivars and therefore also to be consistent in his or her environmental efforts. It further creates a simple basis for communication with wholesalers or retailers. These, in turn, gain greater flexibility in selecting a range of cultivars that meet their customers' needs and in communicating effectively the cultivars' characteristics down the distribution chain (intermediaries, consumers).

By grouping the range of cultivars grown in an orchard into archetypes, it will be easier for the producer to see where there is room for expansion or innovation in planning the future range. Table 22.5 shows how the new cultivars suited to organic production compare in their flavour, i.e. where each of the cultivars susceptible to disease can be exchanged with robust cultivars.

22.13 Soil Management and In-row Weed Control

22.13.1 Sensitivity to weed competition

Fruit trees in commercial orchards are fairly shallow-rooted. Young trees, in particular, spread their roots mostly in the topsoil layer, which is rich in nutrients and organic matter. If this zone is also utilized by other plants, the fruit trees will have to compete for nutrients and water, which – depending on the severity of competition – can lead to a significant reduction in performance. This results not only in short-term yield reductions but also in less growth on branches and fruiting spurs, less root mass and a reduction in both quantity and quality of fruit buds, which are so important for the following year. Hence, strong weed competition often only has an impact on the yield in the following year. These complex and time-lagged linkages require skilful methods of weed control and are a major challenge to fruit growers.

Soil management in organic fruit production has two principal aims: to support and maintain soil fertility (biological activity and physical stability); and to supply the trees with nutrients and water in appropriate quantities and at the appropriate time (basic

Table 22.5. Grouping of apple cultivars into six archetypes and three flavour groups ^a

Archetype (AT)	Definition	Cultivars suited to organic production, listed in approximate order of ripening ^b	Additional cultivars	Flavour group (colour and text on packing label)
'Golden' AT	Yellow, big, smooth skin, low in acidity, predominantly sweet	' <u>Resista</u> ', 'Delbard Jubilé', ' <u>Goldrush</u> ', ' <u>Goldstar</u> '	'Golden Del cious'	YELLOW 'mild to sweet'
'Jonagold' AT	Like 'Golden' AT, but red	' <u>Rubinola</u> ', ' <u>Angold</u> ', ' <u>Viktoria</u> ', ' <u>Delorina</u> ', ' <u>Regne</u> ', 'Pinova'	'Gala', 'Arlet', 'Jonagold', 'Delblush', 'Maigold', 'Fuji', 'Pink Lady', 'Braeburn'	
'Idared' AT	Medium-sized to big, smooth skin, mild, taste balanced in sugar and acidity	' <u>Anwa</u> ', ' <u>Raka</u> ', ' <u>Santana</u> ', ' <u>Idared</u> ', ' <u>Reanda</u> ', ' <u>Florina</u> '	' <u>Satum</u> ', 'Fiesta', 'McIntosh', 'Spartan', 'Berner Rosen', ' <u>Rosana</u> ', 'Jonathan', 'Empire', 'Goster'	
'Cox' AT	Medium-sized to small, rustic appearance, spicy-aromatic, slightly acidic	'Alkmene', 'Discovery', 'Kidds Orange', ' <u>Resi</u> ', ' <u>Topaz</u> ', ' <u>Renora</u> '	' <u>Liberty</u> ', 'Berlepsch', 'Cox's Orange Pippin', 'Kanada Reinette', 'Elstar', 'Rubinette'	RED 'spicy, slightly acidic'
'Gravenstein' AT	Early, for fresh eating, juicy, crunchy, slightly acidic	' <u>Julia</u> ', ' <u>Retina</u> ', 'Primerouge', ' <u>Reglindis</u> '	'Klarapfel', 'Vista Bella', 'Jerseymac', 'Summerred', 'Gravenstein', 'James Grieve', 'Delbard Estival', 'Granny Smith'	
'Boskoop' AT	Pronounced acidity, also for cooking and baking	'Boskoop', ' <u>Rewena</u> ', ' <u>Otava</u> '	'Iduna', 'Glockenapfel'	GREEN 'predominantly acidic, spicy'

^a As of 2 September 1999 (Organic Fruit Production Commission of BIO-SUISSE/F. Weibel, FiBL)

^b Underlined = scab-resistant.

fertilization, supplementary fertilization, control of weeds/cover crops and irrigation).

22.13.2 Soil preparation prior to planting

It is almost impossible to correct major soil deficiencies in existing orchards since, for example, the subsoil cannot be broken up with a deep chisel-type plough. Preparatory

soil-management and soil-restoration measures are, therefore, central to any holistic and efficient soil-management strategy.

One to two years prior to a new planting, the condition of the soil should be assessed carefully so that corrective measures can be taken in time. At this stage, soil improvements can be carried out in the most efficient way. Approaches that can be taken include the following:

- Assess the soil in terms of soil horizons, possibly a spade-sample diagnosis and soil tests.
- Carry out appropriate soil-improvement measures (e.g. drainage, chiselling followed by immediate stabilization by sowing deep-rooting plants, green-manure cover crops, increasing organic-matter content – for example, by adding well-rotted compost, etc.) and, where required, add brought-in, organically approved, slow-release fertilizers to achieve a good nutrient balance (Ca, K, Mg, P). As a guide, the ratio of exchangeable Ca:K should be approximately 10:1 and the K:Mg ratio 2:1. If the K:Mg ratio is higher than 6:1, up to 90 kg MgO ha⁻¹ can be applied annually (Strebl, 2000). Amounts of more than 1 t quicklime (CaO) on light soils and 1.5 t on medium to heavy soils should be split and applied over 2 years. This fertilizer should be applied in the autumn during dry periods.
- The future soil-management system should be planned with optimum mechanization in mind and the orchard layout and planting system adapted accordingly.

22.13.3 Orchard-floor management: controlling ground-cover competition instead of killing weeds

Ground-cover plants fulfil an important function, as their root activity improves the physical structure of the soil and enhances soil biological activity. Ground cover stabilizes the orchard ecosystem by providing habitats for additional species of insects, spiders, etc. Therefore the orchardist should not ask whether it is appropriate to tolerate ground cover at certain times, but rather when it might be necessary to temporarily suppress it. For a long time, orchard soil management was dictated by the 'gardening sentiment' of wanting to control weeds absolutely and no weed was allowed to disfigure the tree row throughout the seasons. In organic fruit production, where no herbicides are used and where, until recently, there were hardly any alternative treatments,

the use of ground covers has almost been too generous. Many organic orchards suffer from too much competition from ground cover

22.13.4 The problem area around the trunk

There are a number of different options for soil management in organic fruit production (Table 22.6). The suitability of a method is determined above all by two criteria; (i) how well the method is adapted to a specific soil, and (ii) how far the area around the trunk is covered. Any type of work carried out around the trunk and the stake is extremely precarious, be it mowing or hoeing, manual work or machines. Working too close to the tree often leads to serious injury to trunks and roots, while working too far away from the trunk means that ground-cover plants can form thick vegetative mats around the tree. This is where voles and field mice find ideal cover. Other important considerations are potential impacts of hoeing passes on soil structure and questions of cost-effectiveness.

22.13.5 The most interesting new developments on the market

Following a period of approximately 5 years of stagnation in the development of methods and machinery for soil management without herbicides, pioneering new developments once again began to appear on the market from 1995 onwards (Plate 22.2). However, in order to optimize sustainable soil management, it is advisable for orchard management flexibly to combine a variety of the methods available, based on the individual situation and the ability to cooperate with other fruit growers.

22.13.6 The Ladurner mechanical hoe

The prototype of this cultivator was built by Bruno Brugger, an organic fruit grower in Friedrichshafen, Lake Constance. The Ladurner Company in Southern Tyrol further developed it for commercial production (Plate 22.2a). The mechanism,

Table 22.6. Different methods of weed control available in organic orchard production

Method	Suitable conditions	Advantages	Disadvantages
Mechanical hoes	Site not too steep; only on soils with stable structure	Quite universal; improves N mineralization in springtime	Can have negative impact on soil structure (allow for regular regrowth of ground cover to revitalize soil structure); area around tree trunk needs to be hand-hoed once or twice a year
Ladurner mechanical hoe (Plate 22.2a)	Where soil is too heavy for other cultivator and sward too dense	Efficient and precise even under difficult conditions; easy to use	Expensive (co-operative use)
Humus-P anet (Plate 22.2c)	Requires somewhat easier conditions (soil, sward) than Ladurner's hoe	Also available as bilateral attachment and with hydraulic width adjustment; in that configuration, highly efficient on light soils	In dense swards, weeds can wrap around and plug the machine, on heavy soils a smear layer may form; 'wavy' demarcation of the traffic way
Eurocomex Joly	Requires somewhat easier conditions (soil, sward) than Ladurner's hoe	Simple machine that can also open up relatively dense swards	Slightly less efficient than Ladurner; more difficult to adjust and to steer
Undercutters (Clemens, Müller and others) (Plate 22.2b)	Only on light soils with a relatively open sward	Simple machine that gives good results on light soils; high speeds are possible (up to 8 km per hour)	Not satisfactory on heavy soils and in dense swards
Disc ploughs (e.g. Spedo) (Plate 22.2d)	More for lighter soils with a good till	Two operations, which can be phased: drawing soil away with feeler-support wheel, 2–3 weeks later throwing soil back with fixed discs and at high driving speed	Only moderate results in the vicinity of the trunk; furrows form in clayey soils
Sandwich system (Plate 22.2g)	Can be used universally	A very simple, inexpensive cultivator is sufficient; easy to use, harmless to trees and soil; combination with mulching machines and other devices. If aisles carry vegetation, additional beneficial insect habitat is provided	Both mechanical hoe and establishment and management of the in-row strip have yet to be improved for commercial application
Flame weeders (Plate 22.2e)	Where cultivators cannot be used because of heavy soils, or used in rotation with cultivators in order to relieve strain on soils	Good impact on emerging weeds, no negative impact on soil structure (ideal supplement to hoeing)	Only limited effectiveness with perennial weeds, energy consumption; open flame can easily damage lower branches and bark of tree trunk

Table 22.6. *Continued*

Method	Suitable conditions	Advantages	Disadvantages
Mulching the in-row strip	Cultivator cannot be used because of site conditions or for operational reasons, mulching material is locally and cheaply available; soil improvement (increase in organic matter desired)	Balancing effect on soil water and nutrient situation; prevents erosion and soiling of fruit; can improve physical and biological condition of soil	Requires a lot of material and is expensive; some manual labour (weeding/mowing) remains; control of voles and mice more difficult
Mulch sheeting (free-draining, heavy-duty) (Plate 22.2h)	Where mice and voles are not a problem; experience in handling sheeting	Always good initial growth; a good long-term solution where it works	Laying, mulching of traffic way, cleaning, repairs and vole and mice control all cause problems; hardly any soil improvement; waste disposal problem
Bark mulch (woodchips are not to be recommended!) (Plate 22.2i)	Only on very free-draining soils; where addition of organic matter is required, where there are few problems with perennial weeds	Improves organic-matter content and soil biological activity; a layer 10 cm thick lasts 3–5 years; application equipment for hire	Ligneous content should be low; can be overgrown by stoloniferous plants
Rape straw	Only where soil is free-draining and where there is a potassium deficiency (200 kg K ha ⁻¹ or more)	Good weed suppression; encourages earthworms and thus improves soil structure and biological activity	Only effective for 1.5–2 years

operational comfort and performance are robust. The results are convincing, even in situations with dense growth and on heavy soils (i.e. conditions under which it is difficult to hoe but which are quite common in fruit production). The hoeing is carried out by two rotors with three tines each. The front rotor, which is slightly smaller, is controlled by a sensor wand and works precisely around tree trunks and stakes. All soil-moving parts are attached to a side-mounted arm moving parallel to the orchard row. This floating position, with lever arms of minimum length and within view of the driver, allows for optimum guidance and control of tillage depth and for straight driving. The significant cost of this cultivator is offset by the fact that it will only have to be used between four and six times a year, so it is perfect for cooperative use.

22.13.7 Thermal weed-control systems

A number of different types of thermal weed-control systems are available. There are variants using several torches with an open flame; systems that pass over the ground with glowing, downward-pointing emitters; and even combinations of open flames for in-row weeding and infrared emitters for the remainder of the area (Plate 22.2e). Branches close to the soil line and the bark of the tree trunk can quite easily be damaged, particularly where flame weeders are being used. Systems that work with hot steam are still at the experimental stage. By their nature, thermal weed-control systems are not as effective in areas of older, dense and matted weed and grass covers, since the heat cannot penetrate down to the lower growing points of the target plants. As long as weeds and grasses are still germinating or

are young, thermal techniques are an efficient alternative to hoeing and are less damaging to soils. Energy consumption has been much reduced in the more modern systems. It is advisable to combine thermal control and mechanical hoeing as, over time, flame-weeding leads to monoculture grass covers

22.13.8 Outlook

The progress made in the development of weed-control systems is most welcome. However, the improved quality of the machines brings with it increased costs. FiBL in Frick, Switzerland, has therefore been working since 1995 on developing an economic alternative, the 'sandwich system' (Schmid and Weibel, 2000; Plate 22.2g). In this system, only two strips, approximately 50 cm wide at a distance of about 12–20 cm each side of the tree trunk, are cultivated. From trunk to trunk a narrow strip of variable width (25–50 cm) with low-growing vegetation remains uncultivated. The two cultivated strips are hoed with a very simple and thus inexpensive device without any separately powered parts. With the 'sandwich system' the overall area of ground that is kept free of weed competition is as large as in a clean-cultivation system and in theory the competition the fruit trees are facing should not be notably different. However, the 'sandwich' method cannot yet be recommended. Both the mechanical hoe and the establishment and management of the in-row strip need to be improved and, even though both trees and yields have developed well so far, the results of specific trials are not yet available. A positive impact on the in-row soil structure and additional beneficial insect habitat in the aisles' species-rich flora are to be expected but have not yet been demonstrated.

22.13.9 Mulching the in-row strip

Mulching can give good results, particularly on light soils and those that are dry in summer or are in need of organic matter (Weibel, 1995b; see Table 22.6)

22.14 Nutrient Management

As in other production systems, the aim of fertilizer use in organic fruit production is to provide nutrients at the correct times and in optimum quantities, in order to achieve a good performance of the trees in terms of both quantity and quality. It is obvious that fertilizer use can only be one of many measures in establishing trees that are physiologically balanced and yield top-quality fruit. For example, if excessive vegetative growth is promoted, the same yield per area will be of lesser quality than if it came from moderately growing trees, because, as a result of strong calcium uptake by shoots, the fruit eventually store less calcium than those from trees with moderate growth. Only when pruning, thinning and fertilizing programmes are in balance can such problems be overcome. However, if the trees are starved of nutrients, their assimilation efficiency and vitality declines, resulting in lowered disease resistance and fruit buds of lesser quality, which in turn lead to lower yields, biennial bearing and a decline in fruit quality. In organic fruit production, soluble, fast-release fertilizers cannot be applied and foliar feeds are only permitted where the need has been demonstrated. A shortage of a particular nutrient, be it as a result of limited availability in the soil or poor conditions for uptake (for example, because of soil compaction or waterlogging), cannot therefore be corrected in the short term.

In order to provide the trees with sufficient nutrients, both in quantity and at the correct times, the fertilizing programme followed by the organic orchardist strives primarily to support soil fertility in a holistic manner. This means that, apart from providing sufficient and balanced amounts of nutrients, the soil structure and soil microbial activity are enhanced and maintained.

A sufficient release of nutrients from organic and organically approved mineral fertilizers can only be achieved when high soil microbial activity allows for the mineralization of fixed nutrients, making them available for root uptake. For this reason, organic standards do not allow, for example, the use of fast-acting lime fertilizers, such as CaO or

slaked lime (Ca(OH)_2), with their caustic effect on the soil fauna.

The soil microfauna itself requires sufficient energy supplies, in the form of organic-carbon sources, as well as a continuity of pore space in the soil up to the soil surface, to ensure gas exchange for respiratory activity. The ideal is a deep, friable soil similar to a forest soil. Soils with ample clay-humus crumbs (friable structure) are characterized by a large internal surface, providing ample cation- and anion-exchange sites for nutrients and a high water-holding capacity. Balanced moisture availability in turn benefits nutrient turnover and water uptake. In such soils the nutrients, their availability, moisture and gas exchange are not just sufficient but also well stabilized (buffered) through numerous interrelationships. Such a stable environment protects roots from stressful conditions and ensures that the trees have access to water and nutrients in keeping with their physiological requirements. The need for corrective applications of single nutrients is thus minimized or eliminated. In order to reach this ideal, organic farming works primarily with organic (farm-yard) manures or green manures

22.14.1 Important helpers in providing nutrients

Earthworms are indispensable for the creation of macropores and clay-humus complexes. The roots of the apple trees, which tend to concentrate in the topsoil level, can penetrate the more dense and less nutrient-rich subsoil levels through the worms' humus-clad tunnels. This increases the utilizable root space. Of the many soil (micro)organisms with their variety of functions, the asymbiotic and associative nitrogen-fixing bacteria are of particular importance. In monocrop leguminous stands, the nodule bacteria can fix 200–400 kg nitrogen $\text{ha}^{-1} \text{ year}^{-1}$ from the air. Mycorrhizal fungi are also important for feeding trees in organic fruit production. They are closely associated with the active root hairs and, in exchange for assimilates, they provide the tree predominantly with

phosphorus (see overview by Marschner, 1995). Phosphorus deficiency practically never occurs in orchards that have a healthy soil (Quast, 1986).

22.14.2 Fertilizer use

Nutrient-withdrawal figures adapted to the current yield situation provide a good basis for calculating the required amounts of fertilizer. Nutrient withdrawal with fruit is relatively small and, at 30 t of apples ha^{-1} , amounts to 20 kg N, 12 kg P, 45 kg K, 12 kg Ca and 4 kg Mg (see Chapter 12). The fertilization programme needs to be based on soil-analysis results and, where deficiency symptoms occur, possibly on leaf-analysis results. In Swiss fruit production, the fertilizer recommendations take into account the physiological (im)balance of the orchard by factoring in additional aspects (shoot growth, cessation of shoot growth, fruit-bud formation, yield, physiological problems, rootstock, soil depth, soil composition and organic-matter content).

22.14.3 Nitrogen fertilization

Supplying nitrogen to apple trees is a problem not so much of quantities but of correct timing. The important phase of nitrogen demand begins before flowering time (i.e. during a time when the soil has hardly warmed up and nitrogen supplies from soil-borne nitrogen mineralization are low). However, during the formation of fruit buds and at the rosette stage, the tree can supply approximately half of its nitrogen requirements from its own reserve proteins (arginine and asparagine in particular) (Faby and Naumann, 1986, 1987; Sanchez *et al.*, 1990). A timely supply of the full nitrogen requirement can therefore well be achieved without actually applying nitrogen fertilizers – for example, by hoeing the in-row winter ground cover before its growth commences (roughly in early April). In this way, the ammonium nitrogen and nitrate nitrogen stored in the sward during the winter, as well as the small amount of

freshly mineralized nitrogen, are made fully available to the trees.

If nitrogen is applied as young composted manure (3–4 months old) or as non-caustic slurry, these applications should be made early in the year (February–March in the northern hemisphere) because of the slow nitrogen mineralization. The maximum application must be limited by the potassium demand of the orchard, as otherwise physiological damage could be induced by an oversupply of potassium. An application of 30–40 m³ or 20–30 t of composted manure ha⁻¹ contains about 50 kg N but also 140 kg K.

Organic standards also permit the use of certain fast-release liquid and solid nitrogen fertilizers. These include horn meal and horn shavings (12–14% N; horn meal takes effect within 10–14 days, while horn shavings take 8–10 weeks), castor-oil meal (5–6% N), blood meal (12% N), vinasse (3.5% N, a by-product of sugar-beet processing), hair or feather meal (13% N), bone meal (6% degreased), amino acid solutions (55% amino acids and peptides, 9% organic N) and oil-seed pulp (4.5–8.5% N). These substances can be particularly useful to fill the springtime nitrogen deficiency mentioned above. However, trial results also suggest caution. Using these fertilizers can easily induce nitrogen imbalances and can give rise to a decline in quality. Soil fertility that is less than optimal cannot be and should not be compensated for by means of fast-release nitrogen fertilizers.

Supplementary phosphorus and potassium fertilizers should only be applied if a need has been ascertained through soil testing. The following phosphorus fertilizers are permitted under organic management: soft ground-rock phosphate, basic slag and aluminium calcium phosphate. Permitted potassium fertilizers include non-chlorinated potassium salt (e.g. kainit), sylvinit, potassium sulphate and potash magnesia (sulphate of potash magnesia, 28% K₂O, 9% MgO).

Permitted liming products include calcium carbonate of natural origin (e.g. chalk, marl, ground limestone, calcareous marine algae), phosphate chalk (gypsum), sugar-factory lime, magnesium and calcium carbonate (e.g. magnesia chalk, ground magnesium limestone).

22.14.4 Soil-improvement products

The topic of nutrient management also covers various soil-improvement products, such as different types of rock dust (e.g. silica-rich volcanic rock dust), seaweed products, products based on brown coal and even so-called 'energy-informed' quartz sand, etc. Unfortunately, the soil-improving characteristics of these products have rarely been demonstrated by independent research, even though there are regular reports from commercial growers that they are happy with them. In the case of seaweed meals, for example, this is quite conceivable, as they contain calcium, organic compounds and many micronutrients in a readily available form, which can spur soil microorganisms as well as plant roots into action.

22.14.5 Foliar feeds and tonics

Organic production strives to feed plants in a harmonious manner by way of a healthy soil and a healthy root system. Foliar feeding is akin to fighting symptoms and should only be used as an emergency measure. Consequently, foliar feeds may only be used if a deficiency has been notified to the certifying body; their use must be registered. The same conditions apply to the use of calcium chloride for the prevention of bitter pit. The following products may be used: magnesium sulphate (Epsom salt) and preparations consisting of sulphates and chelates of iron, boron, manganese, zinc and molybdenum. There are not as yet sufficient trial results to assess the efficiency of foliar feeding with amino acid or vinasse products (see above) for the short-term alleviation of nitrogen deficiencies or for a general improvement of fruit-bud quality. The same is true for so-called tonics. Our recommendation is: (i) in the case of symptoms indicating nutrient deficiency, to immediately carry out a leaf analysis and to send in both affected leaves and leaves of normal appearance of the same cultivar (as a control); and (ii) optimize soil-nutrient supply in accordance with soil-analysis findings and apply foliar feeds in accordance with leaf-analysis findings. Some trees should be left untreated as controls.

22.15 Thinning

The aims of thinning in organic fruit production are exactly the same as in integrated or conventional production (see Chapter 16). Thinning measures aim to reduce the number of fruit per tree to such an extent that all remaining fruit are of optimum quality and that, at the same time, good fruit development is encouraged and biennial bearing is thus avoided. As in conventional production, an early thinning date is desirable – mouse-ear stage until blossom – because of greater effectiveness in preventing biennial bearing. Blossom thinning cannot substitute for fruit thinning after June drop, which is important for quality-fruit formation (Bertschinger *et al.*, 1998). Understandably, organic orchardists take a very careful approach to selectively eliminating flowers, as not only frosts but also pests, such as apple-blossom weevil (*A. pomorum* L.), apple sawfly (*Hoplocampa testudinea* Klug), winter moth (*Omophtera brumata* L.), the moth *Grapholita lobarzewski* Nowicki and diseases such as brown rot (*Monilia laxa* (Ehremb.) Sacc. and *Monilia fructigena* Pers.), blossom blight (*Pseudomonas syringae* van Hall.) and early-season scab (*V. maequalis* (Cke.) Wint.), pose a much greater threat and take more of a toll on blossom and young fruit than would be the case in conventional production.

At present, organic production standards do not allow the use of any growth regulators, including applications for thinning. Manual and mechanical thinning methods are permitted (Plate 22.3). The 'mechanical method' has been in use since the mid-1990s when a resourceful orchardist developed the *Fadengerät* (H. Gessler, Friedrichshafen-Hirschblatt, Germany). This mechanical blossom-thinning device consists of a tractor-mounted, vertically rotating axle carrying a variable number of nylon strings of c. 50 cm length; the angle of the axle is also adjustable. As the tractor moves along the tree rows between the mouse-ear stage and pink-bud stage or even later, the rotating strings damage a proportion of the flowers or cut them off completely. The thinning intensity is thus determined by the number of strings used, as well as by the speed of their rotation

and the tractor speed. Commercial orchards are already fine-tuning this method, based on experience, with a pass on just one side or with very gentle but repeated passes.

This mechanical-thinning tool primarily catches blossom clusters on the periphery of the tree canopy, which are favourable for fruit development, while those with a tendency towards producing poor quality in the centre of the tree tend to escape. Therefore, because of its design, the device is only suitable for very slender tree types with good light penetration into their centres (slender spindles). Apart from the flowers, the nylon strings can also destroy rosette leaves, spurs and the bark of branches. These side-effects, which are also unfavourable from the point of view of assimilation capacity and disease transmission, have to be minimized by way of an observant use of the machine (e.g. use before the unfolding of the rosette leaves) and a tree-training regime adapted to the use of the machine (few vertical branches). The Swiss Federal Research Institute for Fruit Production, Viticulture and Horticulture (Eidgenössische Forschungsanstalt für Obst-, Wein- und Gartenbau) has produced an information leaflet on the use of the *Fadengerät* tool (Bertschinger and Stadler, 1998).

Manual thinning often takes between 100 and, in some cases, as much as 200 man-hours ha⁻¹ and therefore not only is incredibly labour-intensive but also has to be carried out within a very short period. For larger fruit producers, manual thinning without the *Fadengerät* tool is hardly possible, for both financial and logistic reasons.

There are a number of different approaches to manual thinning (Table 22.7; Bertschinger *et al.*, 1998).

22.16 Plant Protection

22.16.1 Aims and principles of plant protection in organic fruit production

It is the organic ideal that plant-protection problems are reduced to a minimum once soil fertility is high and the plant and animal communities are diverse and in harmonious

Table 22.7. Summary of different approaches that can be taken to achieve blossom and fruit thinning of apples under organic production systems.

Method	Suitability criteria, advantages	Disadvantages
Relieve tree of blossom on one side only, leave the other side and apply corrective fruit thinning between June drop and preharvest (Bertschinger <i>et al.</i> , 1998)	Suitability depends on cultivar (it is, for example, more successful with 'Boskoop' than with 'Elstar'). In ideal cases, one-off one-sided thinning has an effect for a number of years It is possible to work with entirely untrained staff	Very labour-intensive and work has to be carried out within a very short time With short-stalked cultivars, for example, fruit clusters that are too dense can remain on the bearing side (crowding, sooty blotch and sawfly attacks, soiling from earwig nests) Young trees can produce too much vegetative growth on the non-bearing side
Thinning to about one blossom cluster every 25 cm	Young trees do not become one-sided. Few problems with short-stalked cultivars	Usually requires specialist staff. In most cases thinning is not carried out thoroughly enough. It is indispensable to calculate the required number of ripening fruit per tree and to count out a sample of blossom clusters (Österreicher <i>et al.</i> , 1998)
Thinning by stripping buds with the back of the secateurs on the topside and underside of the branches	Simple to carry out; can be done during winter pruning and can be carried out by untrained staff Desirable selection for favourably located buds or spurs	Relatively little quantitative control. Early determination of flower set (Floripro, after Dolega <i>et al.</i> , 1997) is recommended
Appropriate winter pruning	Good time in terms of seasonal workload	As yet little experience with this method. Quantitative implementation requires expertise Requires early determination of flower set (Floripro)

balance. In reality, and particularly where it comes to speciality crops, such completely self-stabilizing systems are rarely found. Even in 'well-tuned' decades-old organic orchards, certain pests or diseases can at times get out of control. Therefore, active plant protection is an integral part of organic farming, including both indirect measures that stabilize systems and direct control measures (Table 22.8)

22.16.2 System stabilization as a basic principle

Plant protection in organic fruit production is demanding. Unlike in integrated produc-

tion, sufficiently effective solutions are not available for every problem that may occur. It is, therefore, even more important to utilize the entire arsenal of strategies to promote species-rich biocoenoses, which in turn stabilize the orchard as a whole system. In a system that is as self-stabilizing as possible, individual pests and diseases have a lesser chance of achieving dominance and of causing substantial damage. While this ecological principle is well recognized in theory, it is very difficult to realize in delicate crops, such as a number of fruit species. In some cases this holistic approach can fail because just one of the factors is not optimized (e.g. if a cultivar is used that is highly susceptible to scab or aphids).

Table 22.8. Important pests and diseases in organic apple production, their significance, options for control, and discussion

Problem	Significance	Control options	Discussion
Scab	High	Indirect. Only sunny, well-ventilated sites, well-spaced plants and naturally spreading tree shape; robust cultivars; aid the decomposition of spores by encouraging soil biological activity, spreading well-rotted compost in autumn, flail-mowing fallen leaves. Aim for moderate shoot growth and early cessation of shoot growth	Resistant cultivars strongly on the rise. Susceptible cultivars and use of copper sprays should be done away with as quickly as possible (replaced with clay-powder products). Modern forecasting methods aim to limit the number of treatments required (lesser impact on soils and beneficials)
		Direct. Spray cover must be in place prior to infection period (only protective effect) and must be renewed after heavy rainfall > 20 mm; if necessary into wet foliage during prolonged wet periods. At temperatures < 12°C, clay-powder products or copper (not immediately before or during blossom because of phytotoxicity), at > 12°C wettable sulphur	Scab has been observed on a number of 'disease-resistant' cultivars. In order to suppress the spread of the disease, orchards with disease-resistant cultivars should also be sprayed during the primary time for the release of ascospores (no copper should be used). This can generally be combined with the control of powdery mildew
Powdery mildew	Medium	Indirect. Tolerant cultivars (but resistance to scab should be a priority in the choice of cultivars); aid decomposition of spores, ventilation and cessation of shoot growth	Many of the cultivars that are resistant to scab are strongly susceptible to powdery mildew; in such cases, the control of powdery mildew is particularly important for young trees
		Direct. Manual removal of diseased buds and shoots during winter pruning and as early as possible during the growing season; two to five post-blossom treatments with clay powder or wettable sulphur (scab-control treatments also affect powdery mildew)	
Sooty blotch	Medium	Indirect. Site selection: planting most susceptible (late-ripening) cultivars into the best-ventilated spots. Sufficient air circulation into the centre of the tree; avoiding low-hanging branches, maintain low ground cover	Significance of sooty blotch is increasing in organic production. Major losses often result from insufficiently targeted application strategies and unsatisfactory application methods (sufficient cover with active agent with ample water and high pressure into the centre of trees is crucial)
		Direct. Depending on risk of infection, varying number of treatments with coconut soap (on-site experience, cultivar and	

Continued

Table 22.8. *Continued.*

Problem	Significance	Control options	Discussion
Sooty blotch— <i>Continued</i>		weather) from June onwards; most important applications in late summer until 3 weeks before harvest	
Postharvest disorders	Low	Indirect. Meticulous removal of 'mummies' and rotted fruit from the tree. Avoiding late-season scab infections, fruit damage from pests and contamination through splashing soil or in packaging. Sticking to optimum picking time. Meticulous screening of harvested fruit and good storage conditions. No wet fruit into storage. Direct. Direct measures are not permitted and are unnecessary	Despite the lack of postharvest treatments, there are usually no major postharvest problems with organic fruit if storage conditions are good. Research is being carried out on the use of microbial antagonists
Rosy apple aphid and rosy leaf-curling aphid	High	Indirect. Support for beneficials and cultivar selection. Avoiding root suckers. Direct. Neem preparations before bud break. Other sprays, such as pyrethrums, quassia or soaps, have less effect and only before leaves are curled (pure contact insecticides)	Neem is highly effective and specific in its impact (hardly any impacts on beneficials are known). Even very slight spray drift of neem preparations is highly phytotoxic to pears (susceptibility varies among cultivars)
Woolly apple aphid	High (on the increase)	Indirect. Supporting beneficials: overwinter branches with woolly aphids that have been parasitized upon by the woolly apple aphid parasitoid <i>Aphelinus mali</i> Halld. in a sheltered place and release during warm period in springtime. Choice of cultivars and rootstocks. Avoiding overvigorous trees and damage to trees. Direct. At present no organically acceptable treatments can be recommended. Combined approach of sticky bands at base of tree to stop movement of larvae, removing colonies by high-water-pressure sprays (possibly with addition of soap as wetting agent) or brush, delayed dormant applications of oil emulsions can be useful (plan with adviser)	Cyclical variations in emergence are dependent on the development of the woolly apple aphid parasitoid <i>Aphelinus mali</i> (determined by spring weather conditions)

Table 22.8. Continued

Problem	Significance	Control options	Discussion
Green apple aphid	Low (high in organic tree nurseries)	Indirect. Supporting beneficials, avoiding overvigorous shoot growth Direct. Pyrethrum, rotenone, soap preparations. Restricted to spot treatments where possible, to minimize impact on beneficials	Often held in check by beneficials; set high control threshold in order to minimize impact on beneficials (exceptions are young trees and recently grafted trees)
Red spider mite (<i>Panonychus ulmi</i> Koch), two-spotted spider mite (<i>Tetranychus urticae</i> Koch), apple-rust mite (<i>Aculus schlechtendali</i> Nal.)	Low (occasionally high)	Indirect. Supporting beneficials, cultivar selection, avoiding overvigorous shoot growth, minimizing impact of spray applications on predatory mites (minimum amount of sulphur), releasing shoots or felt bands hosting predatory mites in late summer and autumn Direct. Most important time to control red spider mite is before oviposition, just post-blossom. Soap preparations with large amounts of water, possibly repeating sprays based on counts	Outbreaks particularly in years with warm, dry weather from May to July The use of sulphur impedes the development of both pest and predatory mites Orchards with high species diversity and physiologically balanced trees do not exhibit this problem
Apple-blossom weevil	Low to high (in the vicinity of forests, in years with little blossom)	Indirect. Avoiding locations in the vicinity of forests and woodlands Direct. Where infestation was higher than 10–15% in the previous year and depending on the result of branch-tapping sampling during emergence, a pyrethrum application at > 15°C can be partially effective	Rarely a main cause of reduced yields. Can be a useful 'thinning agent' in years when apple blossom is abundant
Apple sawfly	Medium	Indirect. Supporting beneficials, parasitization has a strong influence on numbers. Manual thinning of first affected fruit prevents attack on further fruit (larva attacks up to five apples) Direct. Quassia extract at petal fall on the basis of the degree of infestation in previous year; white sticky traps during blossom and until fruit set	

Continued

Table 22.8. *Continued.*

Problem	Significance	Control options	Discussion
Codling moth	High	Indirect. Supporting bird populations, parasitization influences appearance Direct. Granulosis virus and/or confusion strategies with pheromones in larger orchards	Granulosis virus is very host-specific and thus not harmful to beneficials. Because of its low UV stability and the moth's long emergence period, granulosis virus has to be applied four or five times where one generation emerges and up to nine times where a second generation also needs to be targeted. Confusion with pheromones only works in larger and isolated orchards
Tortrix moth	Medium	Indirect. Supporting bird populations Direct. Treatments based on the degree of infestation in previous year (monitoring at harvest) with granulosis virus at the balloon stage (stage D/E) and early flowering stage (stage E2)	
Winter moth, tobacco budworm	Low	Indirect. Supporting bird populations, sticky bands to control winter moths in mid-October Direct. <i>Bacillus thuringiensis</i> (Bt) to control young moth larvae between pre- and post-blossom during warm weather > 15°C (otherwise not sufficient feeding activity and Bt ingestion)	Where neem is used to control aphids, its partial effect in controlling winter moths and tobacco budworm should be considered
<i>Laspeyresia lobarzewski</i>	Low to medium	Indirect. Supporting bird populations Direct. Confusion strategy with pheromones in larger orchards	
Voles and mice	High	Indirect. Large-scale improvements to habitats for birds of prey, weasels, foxes and cats. Keeping in-row vegetation and cover along fences low and monitoring regularly. Protective barrier against mice dug into the ground along the fence line or around individual trees Direct. Poisoned baits are not permitted at present. Traps, carbon dioxide fumigation using gas bottles or special equipment. Sanitation is particularly important as part of winter preparations and in the spring	Traps are sufficient for moderate vole populations. Satisfactory control of field mice cannot be achieved at present with carbon dioxide fumigation or trapping

An important criterion in choosing the type and intensity of plant-protection measures is therefore the question of their short-term and long-term impact on the self-regulating forces within the orchard.

The differences between the permitted plant-protection options in organic production and those in integrated/conventional production are as follows.

- There are some pests and diseases for which sufficiently effective treatments do not (yet) exist.
- Only active ingredients and additives to formulations made from plants and minerals may be used (synthetic substances are not permitted).
- The substances are – with a few exceptions – less effective
- The substances only act on contact (i.e. they are not transported in the sap and therefore are not systemic).
- The period of effectiveness of the organic treatments is mostly shorter.

In effect, these differences are of decisive agronomic importance: in converting to organic production, yield stability cannot be guaranteed solely by switching from integrated-production to organic plant-protection products. It is indispensable that the reduced options for plant protection are supported by indirect measures, such as cultivar selection and the provision of habitats for beneficial organisms.

Adapted application methods and regularly maintained and well-adjusted tools are a prerequisite to success in plant protection. For example, spray equipment must be well maintained, as clay powder, where used, increases wear on pumps and nozzles and can leave enhanced filter residues. The fact that the substances used primarily rely on contact activity means that complete wetting is particularly important.

22.16.3 Indirect control measures

The most important indirect measures for pest and disease control are:

- site selection (Chapter 11);
- selection of robust cultivars (Chapter 4),

- provision of habitats for beneficial organisms e.g. with hedges and strips sown in wild flowers and herbs (this chapter),
- supporting and maintaining soil fertility;
- restrained and balanced fertilization (Chapter 12);
- planting and training system resulting in open-structured trees that dry off quickly (Chapter 15).

22.17 Organically Approved Disease-control Products

22.17.1 Clay-powder preparations

Assumed effect: stimulation of induced resistance via phenol metabolism; additionally, aluminium ions released in an acidic environment (pH 3.0–3.5) have a direct impact on germinating spores. Clay powder should not be mixed with alkaline substances, such as, for example, seaweed products, granulosis virus or copper.

Effect on scab and powdery mildew: extensive trials with clay-powder preparations have shown effects just as good as those of the standard fungicide treatments with 1.5 kg copper ha⁻¹ year⁻¹ and sulphur. Since clay-powder preparations are more effective than wettable sulphur at temperatures under 12°C, they are an adequate substitute for copper preparations used at these cooler temperatures. Cultivars that are sensitive to sulphur and susceptible to rusts are more tolerant of these preparations than of treatments with copper/wettable sulphur. Trials have also shown a partial effectiveness against fire blight. Clay-powder applications are not recommended in the summer because of staining and incompatibility with granulosis virus preparations.

In Europe, the experience with 'film-coating' by specially modified kaolin powder (registered in the USA as Surround for pest and disease control) is still insufficient for registration and practical recommendations.

22.17.2 Wettable sulphur

Effect on scab and powdery mildew: the period of effectiveness is dependent on

temperature and is between 6 and 12 days long. At low temperatures not enough control is achieved and at high temperatures over 25°C the period of effectiveness is short (only 4–5 days at 30°C) as a result of elevated evaporation rates. With rising temperatures, application rates need to be increased. Depending on cultivars and the development stage, phytotoxic reactions can occur, such as sunburn, russetting and scorching. The fruit are most sensitive from blossom to T stage (when the calyx cavity and stalk are at right angles). 'Braeburn', 'Cox's Orange Pippin', 'Berlepsch' and 'Granny Smith' are particularly sensitive and the application rate must be reduced by 30%. Sulphur has a partial acaricidal effect. High application rates and short treatment intervals reduce both pest and predatory mite species.

22.17.3 Copper

Controls scab and partially controls European canker (*Nectria galligena* Bres.) and bark canker (*Gloeosporium perennans* Zeller & Childs and *Gloeosporium album* Osterw.). Its biocidal effect results from the copper ions blocking specific enzyme systems in the microorganisms' metabolism. Copper is more effective than wettable sulphur at lower temperatures. Admixtures of copper to pre-bloom applications and possibly to first post-bloom applications are therefore appropriate. Copper applications during bloom can cause russetting. Copper cannot be mixed with clay powder. Copper is a toxic heavy metal for the soil fauna and accumulates in the soil. For this reason, many organic regulations and standards specify maximum application rates (e.g. 1.5 kg ha⁻¹ per annum in Switzerland). EU Regulation 2092/91 makes provisions for a ban on copper preparations in the near future. Copper is available in a number of different formulations (oxysulphate, hydroxide, chloride and others). However, trials have not shown any verifiable differences between the effects or side-effects of these.

22.17.4 Coconut soap

Controls sooty blotch (*G. pomigena* Schw.) and fly-speck (*Schizothyrium pomi* (Mont. ex

Fr.) v. Arx). For sufficient results, the intensity of treatment must be adapted to the risk of infestation in an optimum manner and proper application techniques are indispensable. Coconut soap cannot be mixed with granulosis virus.

22.17.5 Lime sulphur

Lime sulphur is permitted under EU Regulation 2092/91 for organic fruit growing; however, it is not (yet) registered as a plant-protection agent in many European countries. Trials have shown effects of lime sulphur against scab, powdery mildew and sooty blotch and for blossom thinning. Lime sulphur strongly increases the pH on the leaf surface and has a certain curative effect (Trapman and Drechsler-Elias, 2000).

22.18 Organically Approved Products for Pest Control

22.18.1 Plant extracts, soaps and oils

22.18.1.1 Pyrethrum and rotenone

Pyrethrum is a plant extract from a *Chrysanthemum* species; rotenone is extracted from the roots of *Derris* spp. Both are used in apple production to control green apple aphid (*Aphis pomi* de Geer), pear psylla (*Psylla pyri* L.) and, where required, apple-blossom weevil (*A. pomorum* L.). As pyrethrum and rotenone rely on contact activity, pests must be well wetted with the substances and optimum application techniques, with a lot of water and high pressure, are crucial. Both substances have a broad spectrum of efficiency and, depending on their time of use, they can damage certain beneficials. The active agents break down very quickly (half-life of 1–2 days).

22.18.1.2 Quassia

Quassia is a plant extract from 'bitter wood' (a tropical tree species). It is used in apple production to control sawfly (*H. testudinea* Klug) attacks and is partially effective against aphids. It acts as a stomach poison, as well as on contact; the impact on beneficials is low.

22.18.1.3 *Neem extract*

An extract derived from the seeds of the neem tree, which is widespread, for example, in India. The principal active agent is azadirachtin. The proprietary preparation NeemAzal T/S is highly effective against rosy apple aphids (*Dysaphis plantaginea* Pass.) and rosy leaf-curling aphids (different species), albeit with delayed action. It does not control other aphid species. It is partially effective against winter moth (*O. brumata* L.), tortrix moth (*Adoxophyes orana* F.v.R. syn. *Capua reticulana* Hb.) and tarnished plant bugs (different *Lygus* spp.). The impact on beneficials is low. The active agent is absorbed by the leaves and dispersed by way of translaminar flow (the active agent is partly absorbed and distributed within the leaves). Thus neem is effective even if direct contact with the aphids is insufficient (e.g. in the case of curled leaves). Apart from killing aphids, neem also reduces their fertility. With many pear cultivars, even very slight spray drift can cause severe burns to fruit and foliage.

22.18.1.4 *Oil sprays*

Both mineral (paraffin)- and plant-oil preparations are used. Mineral oils are slightly more effective but their degradation takes longer than that of plant oils. Oil sprays are mostly applied at bud break to control scale insects and are also partially effective against red spider mite (*Panonychus ulmi* Koch). However, the latter are more efficiently controlled with soap preparations post-blossom.

22.18.1.5 *Soap-based products*

Soap-based products are manufactured through saponification of natural fatty acids with alkali lye or a sodium hydroxide solution (and therefore fulfil the criterion of being natural products). They are mostly used to control red spider mite and, with lesser effectiveness, aphids. In order to be effective against red spider mite, timing is critical, with applications being made just post-blossom but before oviposition.

Optimum wetting has to be achieved with the applications. The impact on beneficials is low but repeated applications during the summer can cause russetting. Applications during blossom can have a rather unpredictable thinning effect.

22.18.2 *Biological methods*

22.18.2.1 *Granulosis virus*

The granulosis virus occurs naturally, is very host-specific and as a pathogen does not therefore harm beneficial insects. Granulosis virus preparations are used for a highly effective control of codling moth (*Cydia pomonella* L. syn. *Laspeyresia pomonella* L.) and tortrix moth (*A. orana* F.v.R. syn. *C. reticulana* Hb.) on the basis of regionally prepared recommendations for spray schedules. Granulosis virus is a stomach poison. Adding sugar and pine resin extract increases absorption and ultraviolet (UV) stability. Since the larvae are not killed immediately, they can cause small but unobtrusive and usually well-healed bite marks, which do not render the fruit unsuitable for dessert-fruit sales. Granulosis virus cannot be mixed with coconut-soap or clay-powder preparations.

22.18.2.2 *Bacillus thuringiensis* var. *kurstaki* (Bt)

Used to control winter moth (*O. brumata* L.) and small ermine moth (*Yponomeuta padella* L. and *Yponomeuta malinella* Zeller); partially effective against tobacco budworm (*Orthosia* species). Bt is a stomach poison, which is host-specific and therefore not harmful to beneficial insects and predatory mites (e.g. *Typhlodromus pyri* Scheuten). At temperatures below 15°C, feed intake is not sufficient

22.18.2.3 *Traps, pheromones and releases* of beneficials

Scented or coloured traps are used to monitor the emergence or presence of certain pests, such as sawfly (*H. testudinea* Klug) and different moth species, and to control indi-

vidual species, such as bark beetles (*X. dispar* syn. *A. dispar* F.), clearwings (*Synanthedon myopaeformis* syn. *Thamnosphesia myopaeformis* Borkh.) and European goat moth (*Zeuzera pyrina* L.).

Pheromones (sexual attractants) are used to confuse pests and are increasingly used to control codling moth, tortrix moth and the moth *Laspeyresia lobarzewski*. (Even though these are synthetic products, they are mostly permitted under organic standards because they are: (i) identical to natural substances; and (ii) they do not get into direct contact with either plants or soil.) A prerequisite for the use of pheromones is that orchards are relatively large and are isolated from untreated trees and that infestation is not too severe. The border area of the plantation has a higher risk of infestation from females that are attracted into the orchard; it can be protected with additional granulosis virus applications.

Methods involving the release of specially bred beneficials, such as ladybirds for aphids, are still at the research stage.

22.19 Aspects of Farm Management in Organic Fruit Production

At present, few detailed farm-management surveys are available. On the basis of surveys of farm-management records carried out by the FiBL and based on experience it is possible to give the following estimates.

22.19.1 Labour input and direct costs compared with integrated apple production

The sum total of direct costs for the various production aids (e.g. herbicides versus mechanical hoes, systemic fungicides versus wetting sulphur) is roughly of the same order

Training, summer and winter pruning, fruit thinning, aisle mulching, etc. have not been listed in Table 22.9, as there is little difference between the two production systems in the labour input required for these activities.

The main extra burden in organic production is blossom thinning in April/May. Since

Table 22.9. Labour input: comparison of integrated production (IP) and organic production (from Schmid and Mouron, 1997).

Activity	IP holdings (man-hours ha ⁻¹)	Organic holdings (man-hours ha ⁻¹)
Blossom thinning in May	70	70 (annual bearers) 150 (biennial bearers)
Plant protection incl. monitoring	30 (12 applications)	20 (5–9 applications for robust cultivars) 50 (15–20 applications for susceptible cultivars)
In-row management	8 (with herbicide)	25 (mulching, permanent ground cover + area around tree trunk hand-hoed) 45 (6 times for hoeing, once for cleaning around trunk)
Control of voles + mice	5 (poisoned bait)	10–20 (traps, CO ₂ fumigation)
Fertilizing	2 (once per year)	5 (once per year + composted farmyard manure every 5 years)
Harvest	300	270 (c. 15% lower yield but smaller fruit reduce harvesting efficiency)
Grading/sizing	90	90 (lower yield and more tolerant grading rules, but more time-consuming because of higher number of marred fruit and limited mechanical sorting equipment)
		Additional labour in organic production: minimum 0 man-hours, maximum 125 man-hours

during this period the plant-protection measures required are also more labour-intensive (and crucial for success), this is a time of above-normal peak labour demand, particularly on holdings also with livestock enterprises and forage cropping.

22.19.2 Yields

Depending on the individual situation (location, cultivars, planting system) and the expertise of the farm manager, apple yields vary substantially. Surveys conducted during the past few years have indicated 10–30% lower total yields than conventional or integrated production orchards at the same level of production intensity.

The reasons for the lower total yields were:

- larger problems with biennial bearing (manual methods are much more labour-intensive than chemical thinning;

mechanical blossom-thinning tools are as yet not very widespread);

- smaller proportion of high-yielding cultivars, such as 'Golden Delicious' and 'Jonagold';
- more plant-protection problems,
- fewer options for short-term corrections of nutrient deficiencies;
- ground-cover vegetation has a greater impact on the trees' performance (competition for nutrients and water), control is labour- and cost-intensive;
- generally fewer trees per hectare (particularly in older orchards).

The more tolerant grading rules for organic production generally allow for a higher proportion of dessert-quality fruit. In combination with higher prices, strong demand from distribution channels and, in certain cases, public-support payments (e.g. conversion subsidies or agro-environmental payments), the lower yield levels and the higher labour costs can thus be compensated.

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23 Principles and Practices of Postharvest Handling and Stress

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23.1 Introduction

The term 'postharvest handling' encapsulates the many management decisions and processes that are involved in harvesting, handling, storage, packaging and transport of apple fruit necessary to provide the consumer with an acceptable product. Most characteristics that influence acceptance of fruit in the market-place are present at the time of harvest, and include size and shape, colour and freedom from blemishes (Plate 23 1). Internal characteristics at harvest include the presence of or the potential to develop acceptable varietal flavour and texture. Some important

changes that contribute to fruit acceptability occur after harvest, e.g. conversion of starch to sugars. However, postharvest handling is largely concerned with maintaining, rather than improving, quality. Consequently, the management tools used by apple growers, storage operators, packers and shippers are focused on the following:

1. Reducing metabolic rates of processes that result in undesirable changes in colour, composition, texture, flavour and nutritional status.
2. Reducing water loss that can result in loss of marketable weight, shrivelling, softening and loss of crispness.

3. Minimizing bruising, friction damage and other mechanical injuries.
4. Preventing the development of physiological and pathological disorders.

These objectives are met by harvesting the fruit at the maturity stage that will meet the quality standards required by the market either at harvest time or after storage, by handling fruit carefully and rapidly to avoid mechanical injury and to minimize deterioration and by applying protective chemical preservatives (antioxidants, fungicides). Fruit should be cooled quickly to remove field heat, and proper refrigeration should be applied during storage. High relative humidity should be maintained and the storage atmosphere should be controlled. Protective containers and packaging should be used during transport and marketing, along with refrigeration. Good sanitation practices must also be maintained throughout these processes, as well as during harvesting, as outbreaks of food-borne illness can have a devastating effect in the market.

The harvesting of any horticultural product involves the imposition of stress – that is, an interruption, restriction or acceleration of normal metabolic processes. However, many recommended postharvest conditions also cause stress, making the term in a postharvest context somewhat nebulous (Kays, 1997). During postharvest storage and handling, stress is an external factor that will result in undesirable changes in quality if the fruit is exposed to it for a sufficient duration or at a sufficient intensity. However, while recommended storage conditions for apple represent stress to the fruit, to the postharvest physiologist they represent the optimum conditions for maintenance of product quality (Kays, 1997).

The objective of this chapter is to outline the principles and practices involved in postharvest handling and stress. For general postharvest principles, the reader is referred to Kader (1992), Kays (1997) and Wills *et al.* (1998). The effects of cultivar and preharvest management will not be addressed in detail here, but it should be recognized that the responses of fruit to postharvest treatments are greatly affected by these factors. Cultivar, for instance, can influence postharvest man-

agement through effects on ripening rates and physiology. Early-maturing apple cultivars usually produce much higher levels of ethylene than later-maturing ones and have the shortest storage life. Cultivars with lower ethylene-production rates generally have longer storage potential (Watkins *et al.*, 1989b; Gussman *et al.*, 1993; Sunako *et al.*, 1999). Responses of fruit to storage environments are influenced by physiological features, such as diffusion characteristics of the skin. 'Golden Delicious', for example, tends to shrivel faster than other cultivars because of breaks in the cuticle, and the Marshall 'McIntosh' strain is less tolerant to low oxygen in controlled-atmosphere (CA) storage than other 'McIntosh' strains because of higher resistance of the skin to gas exchange (Park *et al.*, 1993). Orchard management practices and climatic conditions have an impact not only on fruit quality at harvest but also on tolerances of fruit to postharvest storage conditions. Examples of the impacts of preharvest factors are provided in this chapter, but the reader is referred to Sharples (1973), Bramlage (1993) and Ferguson and Boyd (2002) for greater detail.

23.2 Fruit Maturity and Ripening

The apple is classified as a climacteric fruit (Kidd and West, 1924). The term 'respiratory climacteric' describes the rise in respiration rate that accompanies the maturation and ripening phase in apple, and this rise is associated with increases in internal concentrations of carbon dioxide and ethylene, respiration and autocatalytic ethylene production (Fig. 23.1). Climacteric fruit can be separated from non-climacteric fruit by responses of respiration and/or ethylene production to exogenous ethylene or its analogues, such as propylene (Wills *et al.*, 1998). In a climacteric fruit such as the apple, ethylene advances the timing of the climacteric, autocatalytic production continues after removal of ethylene and, in contrast to a non-climacteric fruit, the magnitude of the respiratory rise is independent of the concentration of applied ethylene. Thus timing of the climacteric and ripening of apple fruit is advanced by exposure to ethylene.

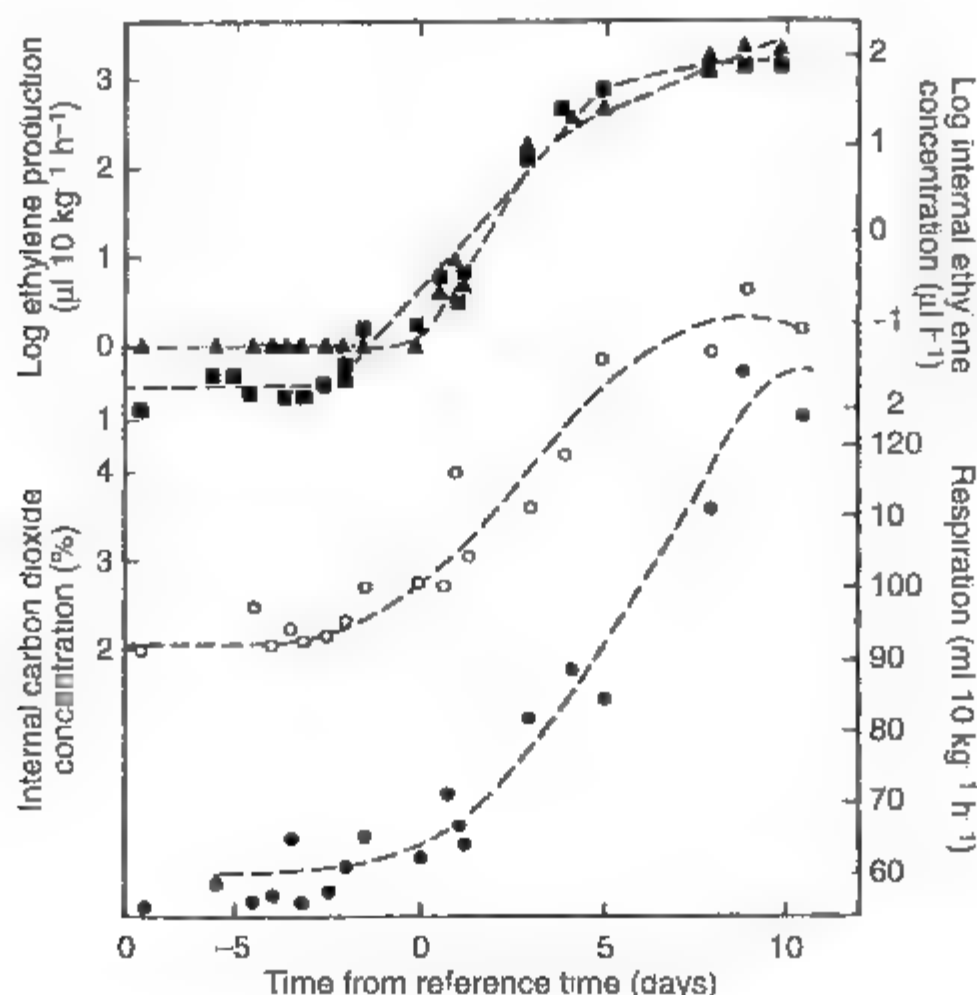


Fig. 23.1. Patterns of ethylene and carbon dioxide concentrations and production in ripening apple fruit (from Reid *et al.*, 1973). Respiration (●), internal carbon dioxide concentration (○), ethylene production (▲), internal ethylene concentration (■).

Ripening of apple fruit involves many physiological and biochemical changes. From an applied perspective, the most important of these are softening, the change of background or ground colour from green to yellow, loss of acidity, conversion of starch to sugars, formation of cuticular waxes and synthesis of aromatic compounds. The metabolism involved in these changes has been described by Knee (1993). In the natural world, these changes result in a desirable product for seed dispersal by the activity of animals and/or breakdown and decay of the fruit. Many of these changes are at least partly desirable for human consumption, and the objective of apple industries is to harvest fruit at the appropriate maturity and apply postharvest technologies to control the rates of these changes in order to provide the consumer with an acceptable product.

23.2.1 Harvest timing and fruit quality

The harvest date within the maturation and

ripening period has a profound effect on the storage quality of fruit. As quality factors such as flavour and aroma of the fruit increase, the storage potential of the fruit decreases (Fig. 23.2) and therefore harvest decisions are a compromise between the quality and storability of fruit. The increases in fruit quality are typically associated with the climacteric. The length of storage of apples can usually be increased by harvesting fruit before they are fully mature, but quality characteristics such as colour and varietal flavour develop less in these fruit, and they can be more susceptible to physiological disorders, such as bitter pit and superficial scald. Fruit harvested over-mature tend to be softer and more easily damaged and may have water-core and be more susceptible to diseases and physiological disorders, such as senescent breakdown.

Superimposed on the relationship between quality and storability during ripening is that between the harvest period and acceptable storage length. The harvest period over which market quality of the fruit

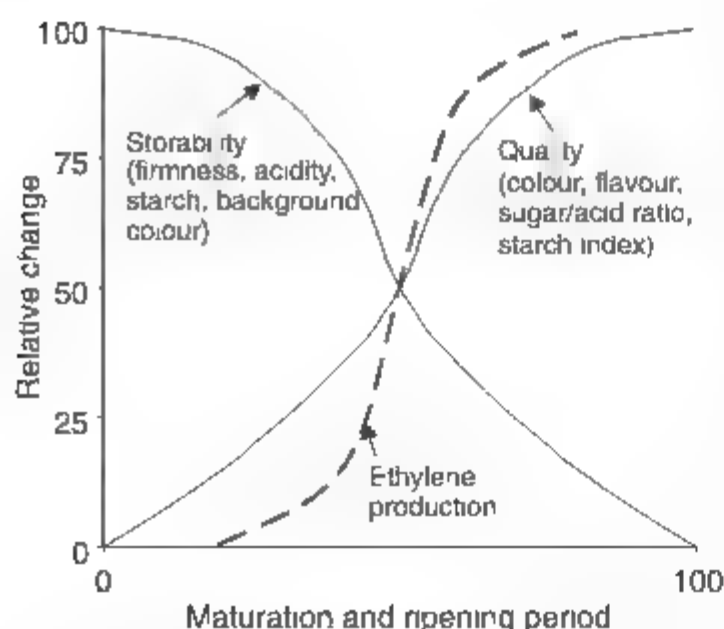


Fig. 23.2. Schematic illustration of the increase in apple-fruit quality during maturation and ripening and concomitant loss of storage potential. An increase in ethylene concentration in the fruit is generally associated with these changes. (Modified from Lau, 1985)

will be acceptable is relatively wide for fruit stored for short periods (1–2 months), but decreases as storage length increases (Fig 23.3). In mature fruit stored for only a month or two, acceptable flavour can develop in early-harvested fruit, while, in those fruit harvested later, flavour is good and fruit are marketable if texture is maintained. In contrast, the harvest window for a fruit that is marketed after long-term CA storage for 9–12 months is much narrower, being limited by failure to develop flavour, loss of texture and development of storage disorders. The actual

harvest periods involved in Fig. 23.3 may be affected by cultivar. For example, the optimum harvest period for an early-season apple, such as 'McIntosh', is much shorter than that for a late-harvested apple, such as 'Rome Beauty'. Therefore, the x axis in Fig. 23.3 might be 1–2 weeks for the former cultivar and 3–4 weeks for the latter one. Regional differences can also be important. For example, the 'Cox's Orange Pippin' apple is a short-term storage apple when grown in New Zealand, but a long-term storage apple in England.

The importance of determining the optimum harvest date for storability will be related to how fruit are utilized and therefore the expectations of the consumer for the product. These expectations vary greatly, depending on the market. Continental Europe, for example, prefers apples at a more advanced stage of ripeness than does the UK (Fidler, 1973). Greater flavour, associated with tree-ripened fruit, is likely to be a premium factor in 'pick-your-own' or gate sales during autumn. In contrast, for long-term-stored fruit, texture is more likely to be a critical acceptance factor, although acceptable flavour must be present. The requirement for a maturity programme generally increases as an industry becomes larger and more complex, especially if it is reliant on long-term storage technology.

Ethylene production of fruit can be manipulated before harvest, either by use of ethephon application to advance ripening (Larrigaudiere *et al.*, 1996; Stover *et al.*, 2003),

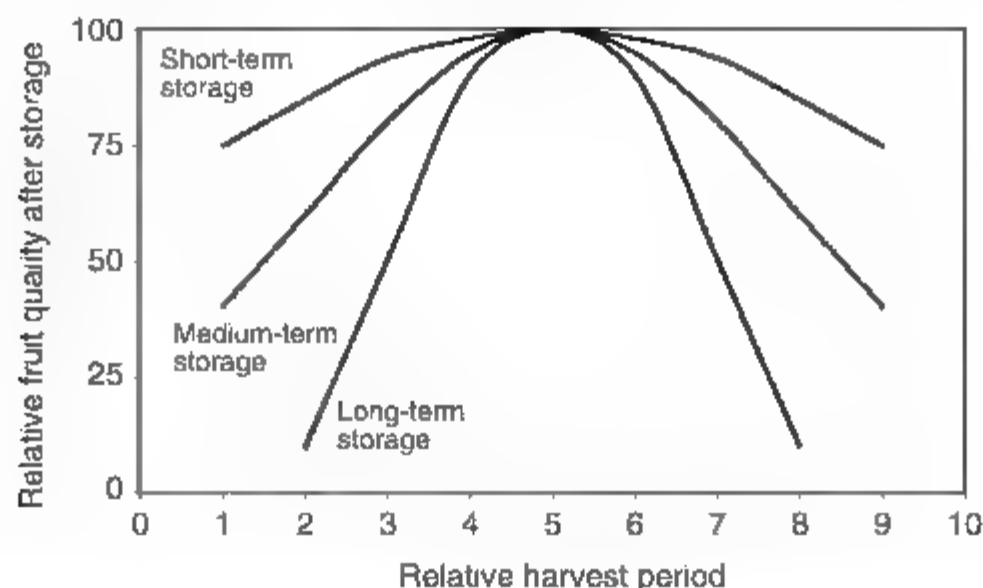


Fig. 23.3. Schematic illustration of the effect of harvest period on storability of apples

or by use of aminoethoxyvinylglycine (AVG), available commercially as ReTain®, to reduce ethylene production and delay ripening (Autio and Bramlage, 1982; Stover *et al.*, 2003). Harvest dates must be adjusted accordingly.

23.2.2 Harvest indices

Many methods have been proposed as indices of apple maturity (Table 23.1). Several

of these are indicators of quality, rather than maturity *per se*. Moreover, harvest decisions have to be based not only on physiological maturity, but also on market requirements, which include factors such as blush, background colour and usually the absence of water-core. Therefore, the term 'harvest indices' is a more accurate terminology for the factors used in making harvest decisions. The most important harvest indices are as follows

Table 23.1. Examples of methods evaluated as indices for determining harvest dates of apple fruit

Harvest index	Reference ^a
Ethylene production or internal ethylene concentration	Diley, 1980; Lau, 1985; Blanpied, 1986; Chu, 1988; Knee <i>et al.</i> , 1989
Respiration	Wilkinson and Sharpes, 1967; Blanpied, 1969; Knee <i>et al.</i> , 1989
Starch pattern index	Reid <i>et al.</i> , 1982; Knee <i>et al.</i> , 1989; Blanpied and Silsby, 1992
Starch content	Knee <i>et al.</i> , 1989
Firmness	Lau, 1985; Knee <i>et al.</i> , 1989
Soluble-solids concentration	Lau, 1985
Firmness and soluble-solids concentration (sliding scale)	Blanpied, 1974
Firmness/soluble-solids concentration × starch index	Streif, 1983; DeLong <i>et al.</i> , 1999
Background colour	Lau, 1985; Watkins <i>et al.</i> , 1993; Plotto <i>et al.</i> , 1995
Calendar date	Blanpied, 1964; Fidler, 1973
Days from full bloom	Haller, 1942; Truter and Humdall, 1988
Heat-unit accumulation	Eggert, 1960
Days from full bloom and temperature records	Luton and Hamer, 1983; Blanpied and Silsby, 1992; Beaudry <i>et al.</i> , 1993
Water-core incidence	Lau, 1985; Blanpied and Silsby, 1992
'T stage'	Stoll, 1968; Faragher <i>et al.</i> , 1984
Flesh colour	Lau, 1985
Seed colour	Lau, 1985
Free sugars and phosphorylated intermediates of carbohydrate metabolism	Knee <i>et al.</i> , 1989
Enzymes (carboxylic ester hydrolase, NADP malic enzyme, β-galactosidase)	Knee <i>et al.</i> , 1989
Peel pigments (chlorophyll, xanthophyll esters, carotenoids)	Knee <i>et al.</i> , 1989
NADPH fluorescence	Cavallieri <i>et al.</i> , 1988
Fruit size	Lau, 1985
Loss of bitter flavour	Blanpied and Silsby, 1992
Separation force	Smock, 1948; Lau, 1985
Titratable acidity	Lau, 1985
Visible/near-infrared spectroscopy	Pers <i>et al.</i> , 2000

^a References are provided as examples only and are not a comprehensive list.
NADP(H), nicotinamide adenine dinucleotide phosphate (hydrogen)

23.2.2.1 Ethylene production or internal ethylene concentration (IEC)

Ethylene, which is an important hormone that affects fruit ripening, can be measured relatively easily by gas chromatography. Since a rise in ethylene production is associated with initiation of ripening, it has been suggested that ethylene production or IEC should be a major determinant of harvest decisions (Dilley, 1980; Lau, 1985). However, the importance of ethylene in making harvest decisions is not straightforward. Relationships between ethylene production and optimum harvest dates can be poor (Blanpied, 1986; Blankenship and Unrath, 1987; Blanpied and Silsby, 1992). Also, the timing, or presence, of increased ethylene production is a function of cultivar and, within a cultivar, is greatly affected by factors such as growing region, orchard within a region, cultivar strain, growing-season conditions and nutrition (Blanpied and Silsby, 1992). Ethylene production may not be relevant for determining the harvest of some cultivars, such as 'Golden Delicious', because it does not increase during the harvest period (Lau, 1985; Chu, 1988; Watkins *et al.*, 1989b). Ethylene production may be a better indicator of when to complete the harvest, especially in cultivars such as 'McIntosh', where autocatalytic ethylene production precedes preharvest drop (Blanpied and Silsby, 1992).

23.2.2.2 Starch test

The hydrolysis of starch to sugars as fruit ripen can be estimated by staining starch with iodine solution. The resulting patterns, which reflect the extent of starch hydrolysis, are rated numerically, using starch charts. Many starch charts are available, either specific to cultivar (Reid *et al.*, 1982; Lau, 1985), or generic (Fig. 23.4). The starch test has become popular because of its ease of use. Optimum starch indices are available for many cultivars and, when the change of indices is linear, the test can be used to predict optimum harvest dates. Indices developed for a cultivar in one region cannot necessarily be applied to other regions. Also, caution is required in interpreting starch pat-

terns, as complications can occur under certain growing conditions. For example, starch indices may appear more advanced than other harvest indices because initial starch accumulation in the fruit was not complete. Therefore, absence of 100% starch staining may suggest incorrectly that starch hydrolysis has already occurred.

23.2.2.3 Flesh firmness

Apples soften after reaching full size and as they mature and ripen (Harker *et al.*, 1997). Flesh firmness has been used as a maturity index, but it is affected by many preharvest factors, including season, orchard location, nutrition and exposure to sunlight, which are independent of fruit maturity (Blanpied *et al.*, 1978; Reid *et al.*, 1982). However, as an indicator of internal quality, it can provide information that is important to fruit performance in storage (Lau, 1985). It can directly affect consumer satisfaction (Liu and King, 1978), and firmness is being used as a quality criterion by wholesalers, especially in Europe, rather than as a maturity index.

23.2.2.4 Soluble-solids concentration

The soluble-solids concentration of apples generally increases as fruit mature and ripen, principally by the conversion of starch to sugars (Brookfield *et al.*, 1997). It is also a quality index, rather than a maturity index, being affected by many preharvest factors, and levels do not necessarily reflect fruit maturity (Reid *et al.*, 1982; Lau, 1985). As with firmness, soluble-solids concentrations are increasingly being used as a quality criterion by wholesalers. Acceptability of apples may be affected by an interaction of firmness and soluble-solids concentration, e.g. a softer fruit with high soluble-solids concentration may be acceptable, whereas the same fruit with low soluble solids is not. Sliding scales incorporating both factors have been developed (Blanpied, 1974).

23.2.2.5 Titratable acidity

Malic acid is the predominant acid contributing to the titratable acidity (TA) of apple fruit. TA decreases during maturation and

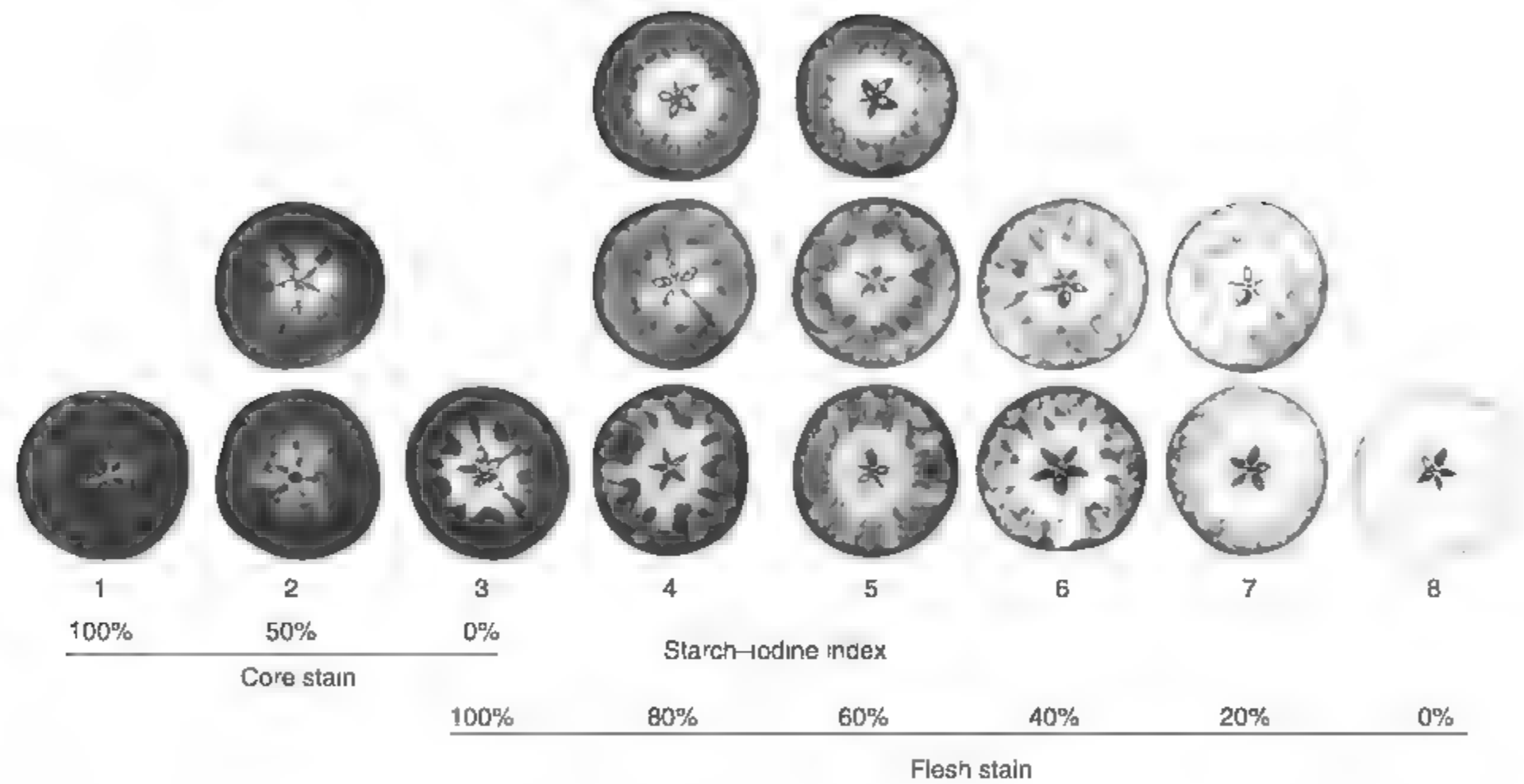


Fig. 23.4. Generic starch-iodine index chart (from Blanpied and Silsby, 1992)

ripening, but optimum values vary by cultivar and season (Lau, 1985).

23.2.2.6 Background or ground colour

As fruit mature and ripen, the background colour changes from green to yellow, reflecting the loss of chlorophyll. Ground colour has been used as a maturity indicator (Smock, 1948; Lau, 1985), but early harvest of fruit for long-term storage may pre-empt the colour changes. Preharvest factors, especially those that affect nitrogen content, can markedly influence chlorophyll concentrations, independent of maturity changes (Lau, 1985). Also, in apples it is sometimes difficult to separate the initial decline of chlorophyll on a surface area resulting from fruit expansion from the subsequent loss resulting from chlorophyll breakdown (Knee *et al.*, 1989). Nevertheless, assessment of background colour is used commonly for bicoloured cultivars, such as 'Gala', 'Braeburn' and 'Fuji' (Watkins *et al.*, 1993; Plotto *et al.*, 1995). Commercially, colour is usually assessed with colour charts, but it is commonly measured experimentally using chromameters.

23.2.2.7 Calendar date, days from full bloom, and temperature records

The usefulness of full-bloom dates and days after full bloom, with and without temperature records, varies greatly by cultivar and growing region (Luton and Hamer, 1983). Calendar dates alone have limited value in regions where temperature variations result in wide differences in bloom dates, but, in more consistent growing regions, days from full bloom can be the most reliable harvest index for several cultivars (Blanpied, 1964; Fidler, 1973). The temperatures during the first 4–6 weeks after full bloom have been useful in predicting a harvest window for 'McIntosh' (Blanpied and Silsby, 1992; Beaudry *et al.*, 1993).

Of the many other indices that have been tested (Table 23.1), their usefulness as harvest indices has been variable, depending on the cultivars and growing regions in which they have been utilized. Seed-colour change, for example, is specific to 'McIntosh', while

flesh-colour changes are used to determine harvest dates for 'Tydemans Red' and 'Spartan' (Lau, 1985).

23.2.3 Maturity programmes

Traditionally, maturity programmes have focused on minimizing wastage resulting from physiological disorders and rotting. However, better attention to nutrition and the use of fungicides has reduced the impact of these factors, and eating quality should now be a major factor in harvest decisions.

Apple-growing regions vary in the type and extent of maturity programmes. IEC measurements and the starch index have become the most widely used maturity indices. Background colour is considered an important harvest index for some bicoloured apples. In some cases, state regulations have been established to set minimum harvest maturities, e.g. the starch index for 'Granny Smith' in California. Firmness and soluble-solids contents, while not maturity indices *per se*, are often measured at harvest, as they can indicate whether fruit will have the market quality required by importing countries such as the UK.

In the USA, New York and Michigan operate apple-maturity programmes in conjunction with their Land Grant universities. Currently in Washington State, individual packing-houses conduct their own maturity programmes in line with their marketing strategies. In each region, a wide range of maturity and quality indices are collected and the optimum harvest period, sometimes called the harvest window, is established for each cultivar (Anon., 1986; Blanpied and Silsby, 1992; Beaudry *et al.*, 1993). The Streif index (firmness/soluble-solids concentration $\times$ starch index), developed by Streif (1983), has shown potential as an indicator for concluding the harvest of several cultivars for CA storage (DeLong *et al.*, 1999).

Some programmes are based on the use of absolute maturity indices, but factors associated with marketing cannot be ignored. It can be argued that the strength of a maturity programme lies not in reliance on absolute maturity indices, but on discussion with

industry personnel on changes in maturity and quality that are occurring over the harvest period. These will include commercial factors, such as colour and susceptibility to bruising. In this way, full participation of extension personnel, growers and storage operators can ensure that fruit of appropriate storage potential are directed towards short-, medium- or long-term storage. For example, in years where fruit maturity is more advanced than usual, but acceptable colour is not present, the rates of harvesting can be increased in recognition of a smaller harvest window for long-term storage.

23.3. Harvesting and Handling

23.3.1 Harvest management

Bruising is a major factor in the downgrading of fruit in the market-place. Most bruising results from impact damage, although compression bruising, which occurs when excessive weight is placed on fruit in containers or when cartons are damaged, can cause fruit loss (Plate 23.2). Impact injury can occur during all facets of fruit handling from harvest to the consumer. These include the following:

1. The harvest operation, where bruising can be reduced by training of pickers, using appropriate picking bags and bins and careful transport of bins from the field to the storage or packing-house.
2. During the packing operation, impacts can occur by fruit-to-fruit contact or by impacts with the grading equipment.
3. Transport of packed cartons of fruit to the market-place and handling of fruit at the retail level (Plates 23.2 and 23.3)

It has been estimated that 40% of bruising occurs in the field, 40% during grading and 20% during transport (Funt *et al.*, 1999). Many factors that affect apple-fruit susceptibility to bruising have been investigated. These have included the effects of orchard-management systems (Baughner *et al.*, 1996), but most focus has been on cultivar, fruit size, harvest date, storage periods, temperature and turgor of the fruit (Klein, 1987,

Samim and Banks, 1993). In general, bruise susceptibility of apples increases with later compared with earlier harvest time and decreases during storage. However, the literature indicates that the effect of each of these factors is inconsistent, suggesting that the importance of each factor may vary according to the particular handling operation.

23.3.2 Postharvest treatments

23.3.2.1 Superficial scald inhibitors and fungicides

Superficial scald is a physiological disorder of apples that develops during cold storage (Section 23.5.1). It was the major cause of fruit loss during storage until the commercial development of diphenylamine (DPA) as a scald inhibitor. Susceptibility to the disorder can be affected by cultivar and can decline with later harvest date. Several major cultivars, such as 'Delicious' and 'Granny Smith', are highly susceptible during normal commercial harvest periods.

DPA is typically applied as a drench, often at the storage receiving point while bins of fruit are still on trucks, or by bin dipping. The concentrations necessary for scald control vary by cultivar, and label rates on proprietary DPA products from commercial suppliers should be followed. Cultivars also vary in sensitivity to DPA-induced skin injury. Several factors that affect DPA efficacy have been summarized by Little and Holmes (2000). Lower DPA application rates may be used if scald risk is lower, for example, because of climate. DPA use can be avoided where cultivars, such as 'Empire' and 'Gala', have a low scald risk.

The use of DPA is widespread, although it is not registered for use in some countries. Adequate control of scald may be obtained by rapid cooling and rapid CA storage, especially low oxygen concentrations, but efficacy can vary according to cultivar and growing region. Alternative means of controlling scald development, for example, stress treatments (Section 23.4.4), have also been investigated because of concern that DPA may become unavailable for this pur-

pose due to consumer concerns about food safety relating to the use of such chemicals.

An additional issue with the use of DPA treatment is that fungicides are also applied in the solution to reduce fungal decay. Fungicides may also be subject to consumer concerns about food safety. Development of pathogen resistance to benzimidazole fungicides is discussed in Section 23.5.2.

23.3.2.2 Calcium

Treatment of fruit with calcium can reduce development of bitter pit, senescent breakdown and rots (Wilkinson and Fidler, 1973; Sharples and Johnson, 1976), and may slow softening (Poovaiah *et al.*, 1988; Saftner *et al.*, 1998). Depending on growing region and cultivar, storage operators will therefore apply calcium, usually as food-grade flake calcium chloride or proprietary formulations. Cultivars vary in susceptibility to calcium-induced skin burn, and product-label application rates should be followed to minimize risk.

Fruit should be treated with calcium immediately after harvest, and it is applied either alone or with DPA (and sometimes with a fungicide). Application is usually by drenching or dipping. Calcium treatment is only commercially effective where disorder incidence is low to moderate, but effectiveness may be improved by CA storage (Ferguson and Watkins, 1989). Factors affecting use of postharvest calcium treatments are discussed by Little and Holmes (2000).

23.3.2.3 Waxes

Apples are commonly waxed with shellac or carnauba-shellac-based coatings during the packing-line operation, although some markets prefer unwaxed fruit. Also, because shellac and carnauba-shellac are associated with non-food uses, such as floor and car waxes, alternative coating materials are being tested (Alleyne and Hagenmaier, 2000).

The main advantage of waxing is to improve fruit appearance. Wax coatings can extend shelf life of fruit, by reducing water loss, respiration rates and ripening (Saftner

et al., 1998). The detergent wash before wax application can also remove dust, dirt and contamination arising from washing in dirty water, which can occur in non-chlorinated hydrohandlers (Little and Holmes, 2000).

23.3.2.4 1-Methylcyclopropene (1-MCP)

Controlling ethylene production and action is a primary goal in the postharvest management of apples, and currently available methods of achieving this are discussed in Section 23.4. However, a new compound, 1-MCP, is now available for many apple industries, under the commercial name SmartFresh™. Registration for 1-MCP was obtained in the USA and other countries in 2002 and European registration is pending. 1-MCP is structurally related to ethylene, has a non-toxic mode of action and is applied at very low dose levels, with low measurable residues in food commodities. The US Environmental Protection Agency has classified 1-MCP as a plant growth regulator.

1-MCP is thought to bind to the ethylene receptor, competing with ethylene for the available binding sites and thereby preventing ethylene action (Sisler and Serek, 1997). Whereas ethylene diffuses rapidly from the binding site after ethylene treatment, this compound remains bound for long periods and formation of an active complex is prevented. Inhibition of ethylene action may eventually be overcome by the production of new receptors (Sisler *et al.*, 1996).

Softening, yellowing, respiration, loss of TA and sometimes a reduction in soluble-solid concentration, as well as the development of several physiological disorders, are delayed or inhibited by 1-MCP application (Fan *et al.*, 1999a,b; Rupasinghe *et al.*, 2000; Watkins *et al.*, 2000). Responses of fruit to 1-MCP may be affected by cultivar and fruit maturity. Volatile production by apples is also inhibited by 1-MCP (Fan and Mattheis, 1999; Rupasinghe *et al.*, 2000). These results are consistent with the view that volatile production is regulated by ethylene, and consumer studies on the acceptability of 1-MCP-treated fruit will be required to ensure that flavour is not unacceptably compromised.

23.4 Storage

Depending on cultivar and growing region, some fruit are stored and marketed for up to a year, when the following year's crop becomes available. Therefore, unless fruit are sold for immediate consumption, the major objective of postharvest management is to decrease the rates of metabolism and thereby the rates of deterioration and quality loss. Commonly, respiratory activity of harvested apples is used as an indicator of metabolic rates. The principal mechanisms available to slow down metabolism are temperature and control of storage atmospheres. Control of relative humidity is also an important component. The interaction of the three factors must be considered in developing a storage regime for any cultivar.

23.4.1 Temperature

Generally, low respiration rates and longer storage periods of apples are directly related to lowered storage temperatures. The lowest temperatures for storage must be above freezing and those at which chilling injury will develop. Maximizing quality maintenance of fruit requires attention to temperature not only immediately after harvest and during storage, but also during packing,

transport and retail display. This combination of events is sometimes described as the 'cold chain', highlighting the importance of maintaining the links from harvest to consumer.

23.4.1.1 Effects of temperature on metabolism

RESPIRATION The respiration rate of fruit is directly affected by temperature (Fig. 23.5) and the respiratory climacteric is suppressed by storage temperatures below 10°C (Fidler and North, 1967). However, respiration of chilling-injury-susceptible fruit may be stimulated by colder storage temperatures, e.g. 'Idared' fruit stored at 0°C initially had lower respiration rates than those stored at 2°C and 4°C but the respiration rate of these fruit increased as low-temperature breakdown developed (Johnson and Ertan, 1983). This effect was exacerbated by lowered oxygen concentrations in the atmosphere (Table 23.2). Increased risk of chilling injuries and of the development of alcoholic off-flavours forms the basis of recommendations for raising storage temperatures when oxygen concentrations are lowered (Table 23.3)

ETHYLENE Low storage temperatures can slow down the onset of ethylene production in apples, but chilling temperatures can also

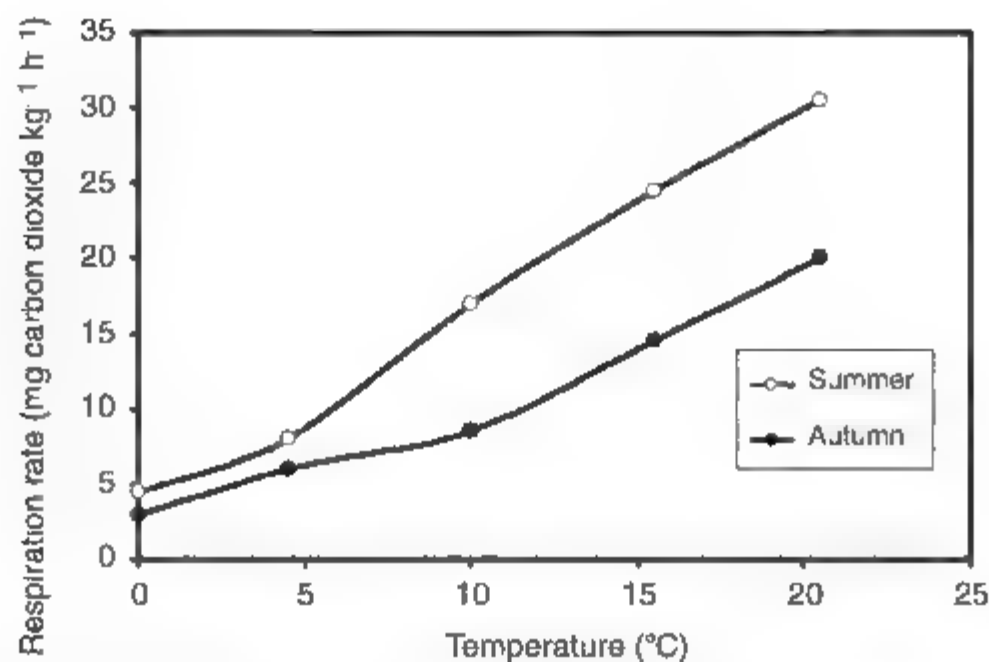


Fig. 23.5. Effect of temperature on respiration rate of summer (early ripening) and autumn (late ripening) apples (modified from Hardenburg *et al.*, 1986).

Table 23.2. Respiration rate and incidence of low-temperature breakdown on 'Idared' stored at 1, 2 or 21% oxygen at 0, 2 or 4°C (modified from Johnson and Ertan, 1983).

Storage temperature (°C)	Oxygen concentration (%)		
	1	2	21
Respiration rate (ml 10 kg ⁻¹ h ⁻¹)			
0	17	18	36
2	11	10	33
4	9	12	35
SED	1.6		
Low-temperature breakdown (%)			
0	73	98	78
2	5	0	0
4	0	0	0
SED	5.1		

Table 23.3. Ranges of atmospheric and temperature conditions for selected apple cultivars (modified from Kupferman, 1997; Watkins *et al.*, 2003). References should be consulted for specific atmosphere and temperature combinations for each growing region.

Cultivar	Oxygen (%)	Carbon dioxide (%)	Temperature (°C)
'Braeburn'	1–3	< 0.5–1.2	0–1.5
'Bramley's Seedling'	1	5	4
'Cortland'	2–3	2–3	0
	2–3	2–3 for 1 month, then 5	2
'Cox's Orange Pippin'	1.2–2	0.7–4	3–4
'Delicious'	0.7–2.5	0–4.5	0–1.1
'Elstar'	1.5–2.5	1–4.5	0–1.5
'Empire'	1.5–3	0.5–3 ^a	1–3
'Fuji'	0.7–2.5	1–2 ^a	0–1
'Gala'	1–3	2–3	0–3
'Golden Delicious'	1–3	2–3	–0.5–2
'Granny Smith'	0.8–2.5	0.5	–0.5–2
'Idared'	1.3–3	0.5–4	0–4
'Jonagold'	1–2.5	2–3	0–3
'McIntosh'	3	2–3 for 1 month, then 5	2
	2	2–3 for 1 month, then 5	3
'Marshall McIntosh'	4–4.5	2–3 for 1 month, then 5	2
'Mutsu'	1.5–2.5	1–3	0–1
'Pink Lady'	1.5–2	1	0

^a CO₂-sensitive so keep CO₂ well below the O₂ level. If not treated with DPA, use 1.5–2% CO₂ during first 30 days.

enhance ethylene production in some cultivars (Knee *et al.*, 1983). Accumulation of 1-aminocyclopropane carboxylic acid (ACC), a key intermediate in the ethylene biosynthetic pathway, and ethylene production of 'Granny Smith' apples at 20°C are markedly increased by exposure to 0°C for at least 8 days, but this does not occur in 'Royal Gala' or 'Delicious' (Jobling *et al.*, 1991; Larrigaudiere *et al.*, 1997). Cold treatment appears to reduce resistance to ripening in 'Granny Smith', and the ripening physiology of this cultivar may be more analogous to that of winter pears.

CHILLING INJURIES Some fruit types, typically tropical or subtropical in origin, develop chilling injury when exposed to storage temperatures below 10–15°C (Saltveit and Morris, 1990). Temperate fruit, though resistant to chilling injury, are not immune to it (Bramlage and Meir, 1990). Most apple cultivars are not sensitive to chilling temperatures and maximum storage life is obtained by storing them as close to 0°C as possible. However, some cultivars are susceptible to the development of chilling-related disorders below 2–4°C. These disorders specifically include low-temperature-related disorders, such as low-temperature breakdown and soft scald, as well as disorders that are aggravated by such temperatures. These disorders are discussed in Section 23.5.1.

23.4.1.2 Cooling after harvest

Because the respiration rate of apple fruit is affected by temperature (Fig. 23.5), the rate of fruit cooling after harvest can markedly influence quality maintenance. Fruit should be removed from exposure to radiant energy in the orchard to refrigeration, or at least shade, as quickly as possible after harvest. However, the importance of rapid cooling varies depending on cultivar, harvest maturity, nutritional status of the fruit and potential storage performance. Early-season cultivars tend to soften more rapidly than those that mature in the later part of the harvest season. Within a cultivar, apples tend to soften more rapidly at later stages of maturity than at earlier stages and in fruit

with high nitrogen and low calcium contents. Rapid cooling appears to be more critical for fruit that are more likely to ripen quickly. Also, the negative effects of slow cooling on firmness and colour are magnified as storage length increases. Therefore, inadequate investment of resources at harvest to ensure rapid fruit cooling may not be apparent until late in the storage period, when fruit may not meet minimum firmness standards for marketing.

The predominant method of cooling apple fruit involves exposing fruit to normal air flow in a refrigerated room. However, this method is slow and inefficient because air flows around, rather than through, bins or cartons of fruit. Slow cooling can result in loss of quality when rooms are filled rapidly and refrigeration capacity cannot cope with large fruit loads. The conversion of many industries to rapid CA storage (Section 23.4.3.3) has also resulted in increased pressure to improve fruit cooling rates.

Faster room cooling of fruit can be achieved by separating and loading bins or cartons into separate rooms for pre-cooling before they are moved into the long-term storage room (modified room cooling) or by loading only the quantity that can be handled by the existing refrigeration system.

Modified room cooling involves increased movement of fruit and logistical planning, but can be extremely useful early in the harvest period when harvest of the faster-respiring early-season apples coincides with the availability of still-empty storage rooms that will be used later. In such situations, where fruit volumes exceed the refrigeration capacity of the cold storage, improved fruit cooling can be achieved by placing no more than two stacks of bins across the width of each CA storage room each day (Bartsch and Blanpied, 1990). In cases where the room is not down to 0°C by the next morning, the number of stacks should be reduced even further to one-deep. Faster cooling will be obtained if bins are placed in the downstream discharge of the evaporator with pallet runners orientated in the same direction as the air flow. Additional bins of fruit should be stacked, no more than two-high, in unfilled refrigeration rooms to cool

overnight before loading into the CA room the next morning. These stacks should be placed randomly throughout the unfilled room to maximize air exchange with the fruit. The capacity to cool fruit is dependent upon the refrigeration capacity and room design.

Forced-air cooling and hydrocooling are less commonly used than room cooling for apples, although forced-air cooling is being used increasingly for cooling of fruit in cartons. In forced-air cooling, bins or cartons are stacked in patterns so that cooling air is forced through, rather than around, the individual container. A slight pressure gradient, usually developed with a fan, forces cold air through the containers, which contain vent-holes placed in the direction that the air will move. Also, minimal packing material that will interfere with free movement of air through the container is used. Direct contact of cold air with the product can cool the fruit 0.1–0.25 times faster than room cooling. The cooling rate is controlled by the volume of air passing over the product, and the economics of cooling are affected by the fan speed and the number of containers being cooled. Water loss from the product is less than that found for room cooling.

In hydrocooling, apple temperatures are reduced by cold water flowing over the fruit surface, by either flooding, spraying or immersion of the fruit in chilled water. The rate of internal cooling is related to the size and shape and the thermal conductivity of the fruit being cooled. The method is simple, economical and effective and avoids water loss, although it is obviously limited to bins rather than cartons of apples.

23.4.1.3 Storage temperatures

The recommended conditions for commercial storage of apples are -0.5°C to 4°C (Table 23.3), the desired temperature being a function of sensitivity to low-temperature-associated injuries (Section 23.4.1.1). However, these disorders typically develop over long-term storage, and sometimes temperatures closer to 0°C are used for short-term (1–2 months) storage of chilling sensitive cultivars to maximize firmness retention

Additional factors in selecting storage temperatures include the interaction between temperature and low oxygen and/or high carbon dioxide concentration (see Section 23.4.3.3). Also, temperature affects humidity requirements – it is easier to maintain relative humidity above 90% at 1°C than at 0°C .

Temperature should be monitored throughout the storage period by measurements at different points throughout the storage room with thermocouples (Bartsch and Blanpied, 1990). It is dangerous to rely on a single thermometer at the door, as temperatures within stacks and throughout the room may be lower or higher than indicated by such readings.

Stepwise change of temperature – for instance, where fruit are kept at 2°C for 4 weeks, 1°C for the next 4 weeks and finally at 0°C , may reduce low-temperature injury and enhance flavour, compared with fruit directly cooled to 0°C . However, storage life under such regimes may be reduced (Little and Holmes, 2000).

23.4.1.4 Post-storage temperature control

While fruit are kept at optimum temperatures during storage, the cold chain is most frequently broken after storage during packing, transport and retail display. When storage rooms are opened for marketing, fruit can be exposed for extended periods to temperatures above optimal due to operations required for movement of fruit for packaging. Fruit temperatures can increase during this time, as well as during packing. After fruit have been packed into plastic bags or trays and placed into cartons, it is important to remove this heat. Passive cooling may take several days because cardboard cartons are good insulators and offer poor air circulation (Fig. 23.6). Moreover, fruit respiration contributes to temperature increases within cartons. Failure to remove heat accumulated during packing processes may be responsible for firmness losses during subsequent storage and transport and have a negative impact on fruit quality at the consumer level (Kupferman, 1994; Watkins, 1999). Forced-air cooling of packed fruit, with modification of carton design to improve air flow over

fruit, resulting in faster cooling (Fig. 23.6), is becoming more common (see also Section 23.4.1.2). A downside of using vented cartons, however, is that fruit can also warm up faster if good refrigeration is not maintained.

Transport requirements for apples can range from simple, involving short distances to a nearby local market, to sophisticated, involving long distances internationally by land and sea. Most transit vehicles have sufficient refrigeration capacity to maintain, rather than cool, fruit. Thus apples should be cooled properly before loading into the

container or other transit vehicle. To minimize warming of the crop and therefore avoid losing the benefits of cooling, it is necessary to ensure fast and efficient loading. Under ideal conditions the loading dock and load assembly areas are refrigerated. Pallets containing cartons should be loaded into transit vehicles in such a way as to allow an air flow that is adequate for temperature control.

Few retail outlets have display refrigeration. Moreover, typical displays in US supermarkets employ stacking of loose fruit, with

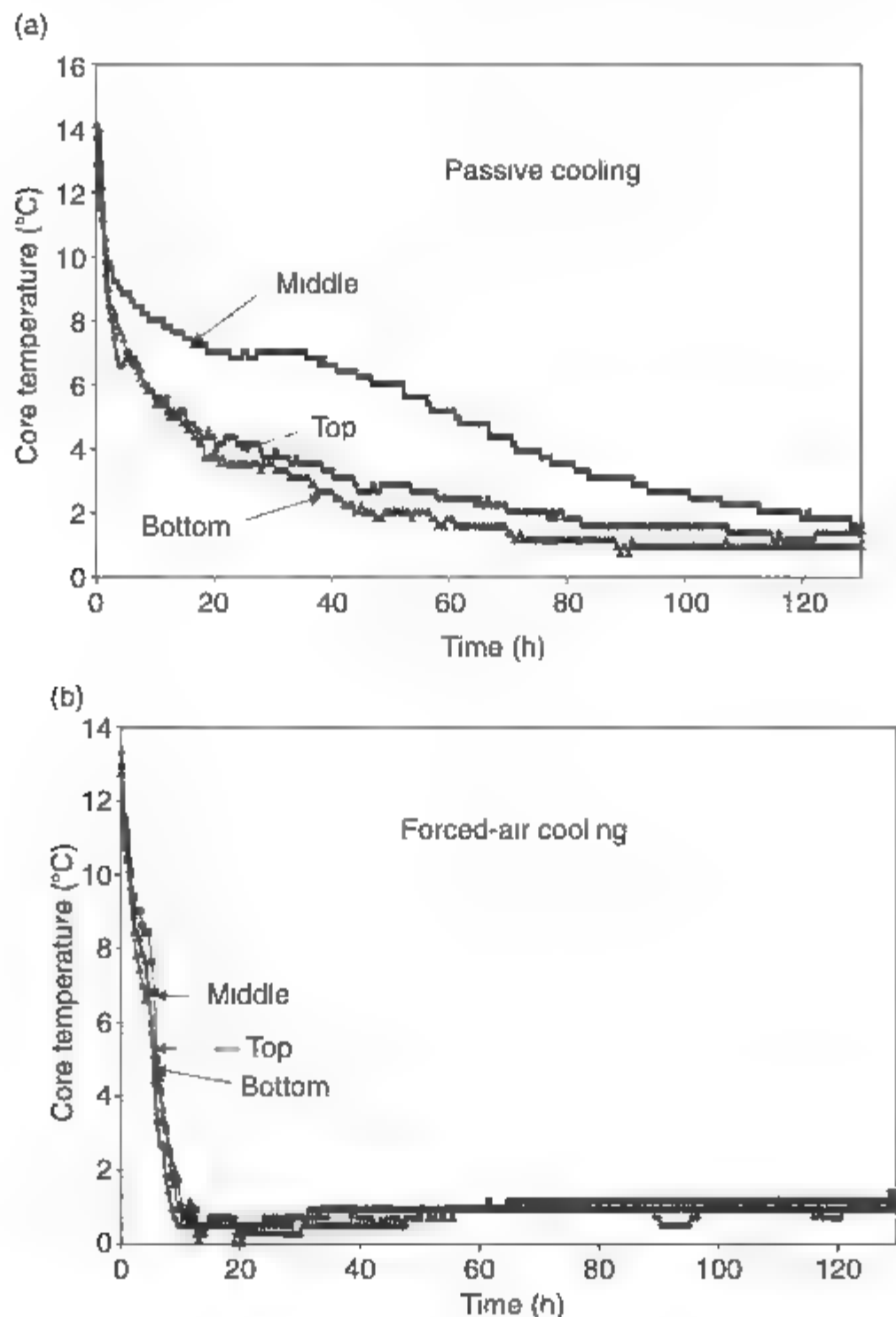


Fig. 23.6. Cooling patterns of apple fruit in cartons within a pallet stack that have been allowed to cool passively (a), compared with forced-air cooling (b). Data are of core temperatures of 'Empire' apples kept in 60 cm × 40 cm export cartons in the top, middle and bottom of stacked pallets. (From Watkins, 1999.)

increased risk of bruising. In the UK, cartons such as the 60 cm × 40 cm box are used more extensively. These cartons have only two layers of fruit and are placed directly on display. As well as reducing the need to handle fruit, more rapid turnover of product minimizes exposure of fruit to elevated temperatures

23.4.2 Relative humidity

Relative humidity is a major factor in preventing moisture loss of apples and therefore maintaining their quality. Relative humidity of 90–95% is recommended for apples to prevent shrivel. The major causes of dehydration of fruit in cool stores are the small surface areas of refrigeration coils and/or frequent defrosting. Therefore, CA rooms should have the largest coil size feasible for the room. The number of defrost cycles can also be reduced to optimize relative humidity in the room, and some operators reduce the oxygen concentration to the minimum safe level and then raise the temperature to 1–2°C to minimize the need to defrost. Storage rooms can be outfitted with high-pressure water-vapour systems that can add moisture to the room and which are suited for operation at temperatures around 0°C. The air-distribution system should be designed to prevent condensation of water droplets on fruit in order to prevent decay. The use of plastic rather than wooden bins or of bin-liners inside wooden bins can also help minimize shrivel – for example, with ‘Golden Delicious’.

23.4.3 Controlled-atmosphere storage

The apple is the predominant horticultural commodity stored under CA conditions. The objective of CA storage is to lower oxygen and increase carbon dioxide concentrations to levels that will maintain fruit quality by decreasing respiratory metabolism and reducing ethylene production and action, but not to levels that induce fermentation or other damaging events. The technology involved in establishing and maintaining CA

storage is outside the scope of this chapter, but readers are referred to Bartsch and Blanpied (1990) and Bishop (1996).

23.4.3.1 Effects of CA on metabolism

RESPIRATION The metabolic rates of apple fruit are reduced by decreasing oxygen and/or increasing carbon dioxide concentrations in the storage atmosphere. The classic studies of Fidler and North (1967, 1968) demonstrated that low oxygen concentrations reduce oxygen uptake and carbon dioxide production proportionally, and therefore the respiratory quotient remains constant. High carbon dioxide concentrations reduce carbon dioxide production more than oxygen uptake, and the respiratory quotient therefore declines under these conditions. Decreasing oxygen concentrations delays the onset of ethylene production in a ventilated system in which low ethylene concentrations in the atmosphere are maintained, but not in a product-generated atmosphere where ethylene can accumulate in the room (Knee, 1980). Decreasing oxygen concentrations also decrease the rates of chlorophyll loss and softening (Table 23.4) and the associated release of soluble cell-wall components, such as uronides (Knee, 1980).

CA may affect respiratory metabolism via effects on glycolysis, fermentative metabolism, the tricarboxylic acid (TCA) cycle or the electron-transport chain, but the extent to which respiration is affected directly or whether other cellular processes whose energy demand affects respiratory rates are slowed is uncertain. Severe stresses resulting from injurious levels of either oxygen or carbon dioxide induce accumulation of acetaldehyde, ethanol and ethyl acetate. In addition, succinate accumulation is a feature of fruit treated with high carbon dioxide concentrations (Hulme, 1956; Fernández-Trujillo *et al.*, 2001), probably because of inhibition of succinate dehydrogenase under these conditions (Shipway and Bramlage, 1973).

ETHYLENE CA storage can also affect ethylene biosynthesis and action, and therefore the effects of CA are not solely due to effects of these atmospheres on respiration (reviewed

Table 23.4. Oxygen effects on ripening of 'Cox's Orange Pippin' apples (modified from Knee, 1980)

Oxygen (%)	Days to lose ¹		
	1 μg chlorophyll cm^{-2} in peel	0.25 μg chlorophyll g^{-1} in flesh	9.8 N flesh firmness
21	90a	83a	61a
10	125b	131b	74b
5	141c	135b	74b
2	242d	230c	85c
1	— ¹	216c	191d

¹ Apparent increase in chlorophyll

Values with uncommon letters are significantly different at the 5% level.

by Watkins, 2002). Ethylene production is reduced by as much as 50% in a 3% oxygen atmosphere (Burg and Thimann, 1959). Burg and Burg (1967) suggested that low oxygen concentrations impeded ethylene binding, but the primary effects of low oxygen are likely to be directly on ethylene biosynthesis, since ACC oxidase, a key enzyme in ethylene biosynthesis, has an absolute oxygen requirement for activity (Adams and Yang, 1979, John, 1997).

The action of carbon dioxide concentrations on ethylene biosynthesis is less clear because: (i) it is difficult to separate the direct effects of elevated carbon dioxide from those of low oxygen concentrations on ethylene biosynthesis; (ii) solubilization of carbon dioxide produces H^+ and HCO_3^- , which may affect the pH of the cytoplasm and consequently enzyme activities (Bown, 1985); and (iii) maximal activity of ACC oxidase *in vitro* requires carbon dioxide and it is uncertain to what extent enzyme activity is regulated *in vivo* by the gas. Burg and Burg (1967) proposed that carbon dioxide displaced ethylene from ethylene receptor sites, but carbon dioxide effects are separable from those associated with ethylene perception (de Wild *et al.*, 1999).

In apples, low oxygen concentrations inhibit only the ACC-to-ethylene step, while high carbon dioxide also inhibits formation of ACC (Li *et al.*, 1983). The fruit have lower internal ethylene concentrations and ACC accumulation in a 2.5% oxygen atmosphere than in air (Lau *et al.*, 1984). Patterns of delayed and decreased ethylene production

of preclimacteric apple fruit in 2% oxygen, 2% oxygen plus 5% carbon dioxide or air plus 5% carbon dioxide, compared with air alone, have been associated with reduced expression of genes encoding ACC synthase and ACC oxidase and of ACC-synthase activity (Gorny and Kader, 1996a). ACC-oxidase activity in air plus 5% carbon dioxide, however, was not different from that in air alone. Primary effects of carbon dioxide appeared to be on ACC-synthase transcription and on accumulation of active ACC-oxidase protein. Fungistatic levels of 20% carbon dioxide or 0.25% oxygen on preclimacteric and climacteric apples have also indicated that ACC-synthase transcript abundance and enzyme activity may be a key step in the inhibition of ethylene production (Gorny and Kader, 1996b, 1997).

23.4.3.2 Factors that affect tolerances of fruit to CA

Two factors affect the tolerance of apple fruit to low oxygen and elevated carbon dioxide concentrations:

1. The resistance of the skin to gas exchange between the atmospheres outside and inside the fruit
2. Metabolic sensitivity to the gases.

The effect of these factors is illustrated by comparing the effects of oxygen on ethanol concentration (used as an indicator of fermentation) in the fruit of 'Delicious' and two 'McIntosh' strains (Fig. 23.7). The 'Delicious' apple is very tolerant to low oxygen, where-

as the 'Marshall McIntosh' accumulates ethanol at higher external oxygen concentrations. 'Red Max' is somewhat intermediate between the others. The skin resistance of the 'Marshall' strain is much greater than that of the 'Red Max' strain, and thus the internal oxygen concentrations in the two strains will be similar at external oxygen concentrations of 2% and 0.8%, respectively (Park *et al.*, 1993). However, differences in tissue sensitivity to low oxygen concentrations between strains also exist, as, even at the same internal oxygen concentrations, ethanol accumulations vary.

The effects of oxygen and carbon dioxide can interact, with fruit sensitivity to low oxygen increasing as carbon dioxide concentrations increase. Sensitivity to both gases is increased by lower storage temperatures and is dependent on cultivar and, within cultivars, on factors such as harvest date (Park *et al.*, 1993). Injuries associated with oxygen and elevated carbon dioxide are discussed in Section 23.5.1.

23.4.3.3 Recommendations for CA storage

The recommended gas composition and temperature conditions for CA storage are specific to cultivar, growing region and sophistication of the equipment available for monitoring and controlling the atmospheres. The wide range of recommended atmos-

pheres, even for the same cultivar (Table 23.3), reflects these factors, as well as different storage strategies employed in different growing regions. Thus, a CA recommendation for a cultivar may not apply everywhere. Regulations on CA storage, covering both the safe operation and the use of the legal definition of 'controlled atmosphere' for stored apples may exist and differ in different states or countries. These regulations include the rate of establishment of CA conditions, the maximum concentration of oxygen permitted and the minimum length of time the fruit can be in CA.

CA technology has undergone major changes in the last 30 years. Old protocols, where CA rooms were loaded over 8–10 days and where fruit respiration then lowered oxygen to 2.5–3% over an additional 15–20 days, are obsolete. 'Rapid CA', in which the oxygen concentration in CA rooms is reduced to less than 2.5% by flushing the atmosphere with nitrogen within 4–7 days from the time of harvest to when CA conditions are applied, is now standard practice for many industries. Some cultivars must be cooled before rapid CA to avoid injury.

The use of rapid CA is critical for long-term (> 6 months) storage. Longer periods between harvest and CA storage can still result in a superior product to that obtained in air storage, but the benefits of CA storage for fruit quality may be lost over time. Even when rooms are filled over extended periods, oxygen concentrations in the CA rooms are usually lowered by nitrogen flushing. It is becoming more common to open rooms briefly to remove some of the fruit for marketing, and nitrogen flushing is used to re-establish atmospheres in resealed rooms.

CA storage regimes fall into one of three categories, depending on the sophistication of equipment and technology involved.

1. Standard CA. Standard CA involves application of conservative atmosphere conditions with a minimum risk of gas-related injuries (Table 23.3). Carbon dioxide concentrations are typically in the 2–3% range and provide additional quality benefits to those obtained by using 2–3% oxygen alone. Control of these atmospheres may be manual

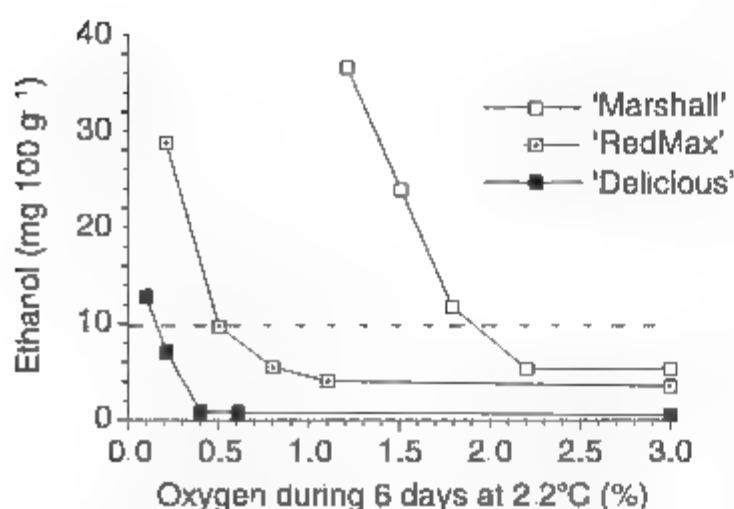


Fig. 23.7. Ethanol concentrations in the flesh of 'Marshall McIntosh', 'Red Max McIntosh' and 'Delicious' apples when kept in different oxygen concentrations at 2.2°C (from Blarpiet and Jozwiak, 1993)

by daily reading and adjustment or via computer-controlled equipment. The margin of safety is large enough when oxygen concentrations are around 2% for fluctuations in gas concentrations found in manually adjusted storage rooms not to cause fruit injury.

2. Low-oxygen CA storage. In low-oxygen CA storage, fruit are kept at oxygen concentrations below 2% but above the concentrations at which fermentation will occur (Table 23.3). In Europe, the term ultra-low oxygen (ULO) is used to describe these atmospheres. The safe oxygen concentration varies by cultivar and growing region. 'Delicious' apples from British Columbia, Canada, for example, can be stored safely at 0.7% oxygen concentrations (Lau, 1997), allowing control of superficial scald without the use of DPA. Fruit of the same cultivar from other growing regions may show injury when stored at these low oxygen levels (Lau *et al.*, 1998). Strains within a cultivar can also vary in sensitivity (Lau, 1997). In general, it is necessary to increase storage temperatures when low-oxygen CA storage is used. The carbon dioxide concentrations under low-oxygen storage are usually much lower than under standard CA, because additional benefits of carbon dioxide for firmness are not observed.

Protocols have been developed to reduce the risk of low-oxygen injury development in regions where susceptibility of fruit to damage appears high. In the north-eastern USA, for example, these include factors such as harvesting fruit early in the harvest period, avoiding fruit with low seed counts, rapidly reducing fruit-core temperatures, raising storage temperatures, avoiding the use of DPA and using automatic gas-analysis and control equipment to eliminate oxygen fluctuations that might lead to low-oxygen injury (Blanpied, 1990).

3. Low-ethylene CA storage. Low-ethylene ($< 1 \mu\text{l l}^{-1}$) CA storage has been evaluated as a method for reducing superficial scald, as a safe substitute for low-oxygen CA storage and for retarding flesh softening and other forms of senescence (Knee and Hatfield, 1981; Blanpied, 1990; Stow *et al.*, 2000). Ethylene is removed by absorption on to

potassium permanganate, by oxidation or by catalytic burners.

Results of this technology for fruit quality have been variable, as low-ethylene CA storage does not maintain quality if concentrations of ethylene gas within the fruit cannot be controlled. Because of the resistance of the skin to diffusion, it is possible to have high concentrations of ethylene within the fruit, with consequent effects on ripening, even when concentrations in the storage atmosphere are low. Therefore, the technology is limited to naturally low-ethylene-producing cultivars such as 'Empire', and/or to early-harvested fruit to ensure that only preclimacteric fruit are stored. Loss of firmness, but not colour, may be delayed by low-ethylene CA storage (Stow *et al.*, 2000). The return on investment in this technology for maintaining fruit quality has not been adequate. However, reduced superficial-scald incidence by lowering ethylene, even when concentrations are above $1 \mu\text{l l}^{-1}$, in CA storage (Knee and Hatfield, 1981) could be useful if DPA is no longer available to the apple industry.

CA technologies, as well as associated marketing strategies, will continue to develop. For example, decreasing periods of acceptability for air-stored fruit, especially of softer cultivars, such as 'Cortland' and 'McIntosh', are resulting in increasing use of short-term CA. This type of storage is occurring even though storage time of fruit under CA does not meet regulatory requirements for labelling the fruit as being 'CA-stored'. CA can also be used during shipping, either using modules that maintain atmospheres in ships' holds or by use of CA-fitted containers (Bishop, 1996). Apples are a relatively low-value commodity, however, and the utilization of new and existing technologies is influenced greatly by cost-effectiveness. In some regions, sophisticated technologies are not required to meet market demands, whereas, in others, investment in these technologies is the cost of staying in the business.

Modified-atmosphere (MA) storage, in which atmospheres around the fruit are modified passively by polymeric-film bags, has been tested for both transport and wholesale purposes (Hewett and Thompson,

1989; Geeson *et al.*, 1994; Watkins *et al.*, 1997a), but have been used on only a limited scale commercially. The major impediments to their use include additional cost of the films, as well as those associated with the logistical requirements of training the packers, sealing of bags and preventing damage to bags

23.4.4 Stress treatments

There has been increasing interest in short-term stress treatments, such as low oxygen and high carbon dioxide concentrations that are outside the normal range for storage, and heat, for maintenance of quality and disease control and to meet quarantine requirements. This research has been prompted, for example, by the search for non-chemical substitutes for chemicals, such as DPA and fungicides. These treatments, which may be applied immediately after harvest or intermittently during storage, are suitable only if the tissue recovers without damage after removal from storage.

23.4.4.1 Low-oxygen stress

Initial low-stress treatments of 0–0.5% oxygen for 5–10 days control the incidence of superficial scald and the losses in firmness and colour of 'Granny Smith' (Little *et al.*, 1982). Inhibition of superficial scald development by initial oxygen stress has also been shown for other cultivars, and it may be possible to devise treatment strategies appropriate to the cultivar and length of storage period (Wang and Dilley, 2000). The limitation to commercial adoption of initial low-oxygen stress treatments may be seasonal variations in cultivar response, and the associated risk of fermentation.

23.4.4.2 High-carbon-dioxide stress

Commercially, concentrations of 10–20% carbon dioxide were used to maintain flesh firmness of 'Golden Delicious' grown in Washington State (Couey and Olsen, 1975), but risk of carbon dioxide injury development limited the use of this method to other regions or to other cultivars (Bramlage *et al.*,

1977; Lau and Looney, 1978). Also, early research showed that treatment of fruit with 30–60% carbon dioxide inhibited superficial scald development (Pieniazek *et al.*, 1946), but benefits are limited, especially as risk of carbon dioxide-induced injury may be high (Fernández-Trujillo *et al.*, 2001).

23.4.4.3 Heat treatments

Heat treatments, applied either as hot air (e.g. 38°C for 3–4 days) or as short-term hot water (e.g. 40–50°C for up to an hour), inhibit softening of apples and delay development of superficial scald during storage (reviewed by Lurie, 1998). However, heat treatments can accelerate the rate of degreening. While hot-water treatments may be suitable for quarantine treatments, commercial implementation for apple fruit may be hindered by the relatively small margin of safe temperatures that do not result in damage, expressed as skin browning and internal breakdown (Smith and Lay-Yee, 2000).

23.5 Physiological and Pathological Disorders

23.5.1 Physiological disorders

Given the extended storage periods and the many cultivars that exist, it is not surprising that a wide variety of physiological disorders have been identified in apple fruit. Susceptibility to disorders varies by cultivar, preharvest factors and postharvest conditions (Smock, 1977; Snowdon, 1990; Blanpied *et al.*, 1999; Little and Holmes, 2000).

Disorders can be considered in three categories:

1. Disorders that develop only on the tree. The most important of these is water-core, in which intercellular air spaces in the core and cortical tissues become filled with liquid, predominantly sorbitol (Marlow and Loescher, 1984). Usually the occurrence of water-core is associated with advancing fruit maturity and low night temperatures prior to harvest, but a variant of the disorder can occur as a result of heat stress. In 'Fuji', its occurrence and type of development can be

affected by growing region (Harker *et al.*, 1999). Presence of water-core in fruit at harvest creates problems in certain cultivars, such as 'Delicious', because fruit with moderate or severe water-core can later develop breakdown during storage. Therefore, occurrence of water-core in 'Delicious' is an indicator of the end of the harvest period (Blanpied and Silsby, 1992). In contrast, water-core is desirable in the 'Fuji' apple because of the sweetness it imparts to the fruit, and mild or moderate water-core does not appear to result in the development of breakdown (Watkins *et al.*, 1993). Grade standards for 'Fuji' have recently been modified so that water-core is not a grade defect for the cultivar in the USA or Canada.

2. Disorders that develop on the tree and during storage. Bitter pit is a disorder characterized by development of discrete pitting of the cortical flesh, the pits being brown and becoming desiccated with time (Ferguson and Watkins, 1989). The pits may occur predominantly near the surface or deep in the cortical tissue. An associated disorder, known as lenticel blotch, is also observed in some cultivars, such as 'Braeburn' and 'Delicious'. Sun-scald, another disorder, occurs in fruit on the tree, but browning/blackening of the skin develops in storage.

3. Disorders that develop during storage. These can be divided into senescent breakdown disorders, chilling disorders and disorders associated with inappropriate atmospheres during storage. The most common disorders associated with temperature and atmospheres are superficial scald, soft scald, low-temperature breakdown, brown core, internal browning, low-oxygen injury and high-carbon-dioxide injury. Several other disorders have been described (Blanpied *et al.*, 1999).

Because of their commercial importance, factors associated with the development of common physiological disorders are briefly summarized.

23.5.1.1 Bitter pit

The incidence and severity of bitter pit are affected by cultivar, but within a cultivar bitter pit is related to harvest date and climate

(Ferguson and Watkins, 1989). In susceptible cultivars, harvest of less mature fruit can result in higher bitter pit incidence, as can excessive pruning or high temperatures and/or water-stress conditions during the growing season. Influences of climatic conditions are at least partly related to their effects on calcium concentrations in the fruit.

Development of bitter pit during storage results in financial loss, and a number of strategies have been employed to prevent its occurrence. Preharvest calcium sprays are commonly applied to reduce bitter pit development (Ferguson and Watkins, 1989). Methods to predict bitter-pit-susceptibility risk based on mineral concentrations (mainly low calcium) at harvest (Ferguson and Watkins, 1989) or infusion of magnesium (Burmeister and Dilley, 1994) have been developed. Rapid cooling and CA storage may also reduce its development during storage, but most focus has been on postharvest application of calcium to fruit (Sharples and Johnson, 1976). Calcium drenches are commonly applied to bitter-pit-susceptible cultivars and in the USA are routinely applied with DPA. Vacuum infiltration of fruit with calcium was used commercially in New Zealand for several years but has now been phased out. Neither drenches nor vacuum infiltration will totally control bitter pit in highly susceptible apples (Ferguson and Watkins, 1989; Hewett and Watkins, 1991), and good preharvest management practices that reduce risk of subsequent disorder development should be stressed.

Recommended rates for pre- and postharvest application of calcium vary by cultivar and region. Therefore product labels should be followed, in conjunction with the advice of the local extension specialist.

23.5.1.2 Senescent breakdown

Senescent-breakdown incidence is related to the harvesting of overmature fruit and/or fruit with low calcium concentration (Marmo *et al.*, 1985). It can be exacerbated by storing fruit at higher than optimal temperatures. Fruit that are susceptible to breakdown because of low calcium are commonly drenched with calcium salts before storage

(Sharples and Johnson, 1976), but the incidence of senescent breakdown can also be reduced by harvesting fruit at a less mature stage, rapid cooling and reducing the duration of storage. Increased senescent-breakdown incidence was shown to be related to the climacteric in one study (Wilkinson and Sharples, 1967), but not in others (Blanpied, 1969; Blanpied and Silsby, 1992). However, because the occurrence of breakdown is highly dependent on calcium concentrations in the fruit (Marmo *et al.*, 1985), the ability to detect relationships between the disorder and the climacteric may be confounded. A fruit with high calcium concentrations may never develop senescent breakdown, while one with low calcium concentrations may show increased disorder incidence with later harvest dates (Watkins *et al.*, 1989a).

23.5.1.3 Superficial scald (*syn.* storage scald)

Superficial scald is a physiological disorder associated with long-term storage (Wilkinson and Fidler, 1973; Ingle and D'Souza, 1989). It was the major cause of apple-fruit loss until the advent of postharvest treatment with the antioxidant DPA. Cultivar, climate and harvest date affect susceptibility of fruit to the disorder (Wilkinson and Fidler, 1973; Emonger *et al.*, 1994).

DPA is usually applied with a fungicide to reduce decay incidence, and calcium salts may also be included at the same time to reduce bitter pit or senescent breakdown. Both DPA use and DPA residues on imported fruit are prohibited in some countries. Another antioxidant, ethoxyquin, is no longer permitted for use on apples.

Alternative ways of controlling superficial scald are being investigated, and storage operators are reducing the use of DPA where possible. Low concentrations of oxygen in CA storage reduce the risk of scald developing and may also permit the use of lower DPA concentrations. Low-oxygen and low-ethylene CA storage also reduce scald incidence. In British Columbia, Canada, 0.7% oxygen storage is used as a substitute for DPA treatment (Lau, 1997). This technique cannot be used universally

because fruit grown in other regions may be susceptible to low-oxygen injury (Lau *et al.*, 1998).

23.5.1.4 Low-temperature disorders: soft scald, low-temperature breakdown, brown core and internal browning

Soft scald is characterized by irregular but sharply defined areas of soft, light brown tissue, which may extend into the cortex (Snowdon, 1990). Susceptibility of fruit to soft scald is cultivar- and climate-related, and disorder incidence may be aggravated by harvesting overmature fruit and delays between harvest and cooling. Storing fruit at 3°C rather than at lower temperatures can sometimes control the disorder (Snowdon, 1990), and DPA, used for the control of superficial scald, may also reduce the incidence of soft scald (Wills *et al.*, 1981). Storage at a lower temperature following prompt cooling can reduce the incidence of soft scald on 'Golden Delicious' fruit.

Low-temperature breakdown, brown core and internal browning are affected by cultivar sensitivity to low temperatures and generally these disorders increase in incidence and severity as the length of storage is increased (Wilkinson and Fidler, 1973). Climate affects the sensitivity of fruit to the disorders, with more problems occurring after colder, wetter growing seasons. Low-temperature breakdown is characterized by markedly brown vascular bundles, browning of flesh and a clear halo of unaffected tissue underneath the skin. In contrast to senescent breakdown, the affected tissues are more likely to be firmer, more moist and darker in colour. Brown core (*syn.* core flush) involves browning of the flesh, initially in the core area and later in the cortex, where it becomes difficult to distinguish from low-temperature breakdown. Internal browning does not involve the breakdown of the flesh but rather a greying of the flesh apparent when the apple is cut. Internal browning and core flush are often associated with higher concentrations of carbon dioxide, since both can occur in CA when the carbon dioxide concentration is higher than that of oxygen.

23.5.1.5 Low-oxygen injury

Low-oxygen injury affects fruit in a number of ways (Wilkinson and Fidler, 1973; Snowden, 1990; Blanpied *et al.*, 1999). The first indication of injury is loss of flavour, followed by fermentation-related odours. These odours may disappear if storage problems are identified soon enough and severe injury has not occurred. Injury symptoms range from purpling or browning of the skin in red-coloured cultivars, development of brown soft patches resembling soft scald and abnormal softening and splitting of fruit. As discussed earlier, cultivars vary greatly in response to low oxygen, and susceptibility to injury is influenced by a number of pre- and postharvest factors.

23.5.1.6 Carbon dioxide injury

Carbon dioxide injury may be external or internal. The external form consists of wrinkled, depressed colourless or coloured areas restricted to the skin surface and usually on the greener side of the fruit. Internal forms are expressed as brown heart and/or cavities in the flesh (Wilkinson and Fidler, 1973). Occurrence of the disorders is cultivar-specific, and generally external carbon dioxide injury is associated with early harvest, while that of internal injury is associated with later harvest. The growing region also affects susceptibility of fruit to carbon dioxide injury (Bramlage *et al.*, 1977; Elgar *et al.*, 1999).

Susceptibility to carbon dioxide injury has long been a problem for certain apple cultivars. It is the basis, for example, for the commercial CA recommendations for 'McIntosh', in which carbon dioxide levels in the storage atmosphere are kept to 2–3% for the first 4–6 weeks and then allowed to increase to 5% (Watkins *et al.*, 2003). Several newer apple cultivars, including 'Empire', 'Fuji' and 'Braeburn', appear to be susceptible to carbon dioxide (Watkins *et al.*, 1997b; Elgar *et al.*, 1998; Volz *et al.*, 1998), resulting in commercial losses. Carbon dioxide injuries have occurred in air-stored fruit under conditions where carbon dioxide can accumulate (e.g. warm fruit in sealed cartons)

At least in the case of 'Empire', losses due

to carbon dioxide injury have occurred when DPA usage has been stopped because the cultivar is not susceptible to superficial scald. It was not previously recognized that DPA reduced the incidence of both external and internal carbon dioxide injuries (Burmeister and Dilley, 1995; Watkins *et al.*, 1997b; Fernández-Trujillo *et al.*, 2001). These observations highlight the point that chemicals that are technically applied for one reason may also have other effects that may not be appreciated until the chemical is withdrawn from use. Non-chemical strategies to reduce carbon dioxide injury include acclimatization of fruit in air before CA storage, if this can be done without loss of quality, and initially maintaining low carbon dioxide concentrations in the storage environment (Wang *et al.*, 2000).

23.5.2 Pathological disorders

The main postharvest diseases of apples that develop in storage are blue mould, caused by *Penicillium* species, and grey mould, caused by *Botrytis cinerea*. *Mucor pyriformis* Fischer can cause severe losses in pears but is less common in apples. *Botrytis* and *Penicillium* species enter fruit primarily through cuts, stem punctures and bruises, but *Penicillium expansum* Link can invade some apple cultivars via the stem during long-term CA storage (Rosenberger, 1999). Other pathogens of stored apples include the *Colletotrichum* species that cause bitter rot, the *Botryosphaeria* species that cause black rot and white rot and *Pezizula malicorticis* (Jackson) Nannf., the cause of bull's-eye rot (Rosenberger, 1990). Decays caused by *Collectotrichum*, *Botryosphaeria* and *Pezizula* are initiated in the field and must be controlled by using fungicides or other disease-management strategies during the growing season.

Blue mould and grey mould are usually controlled during long-term storage by postharvest application of the benzimidazole fungicide, thiabendazole (2-(4-thiazolyl)benzimidazole (TBZ) (Mertect 340F, Deccosalt 19), applied in combination with DPA (Hardenburg and Spalding, 1972). TBZ may

be applied a second time as a line spray or in wax as apples are packed. Benzimidazole-resistant strains of *P. expansum* and *B. cinerea* were discovered in apple storage during the mid- to late 1970s, but TBZ plus DPA continued to control blue and grey moulds, because most benzimidazole-resistant strains of the pathogen were highly sensitive to DPA (Rosenberger and Meyer, 1985). During the mid-1990s, the incidence of blue mould began to increase in some apple packing-houses where the predominant strains of *P. expansum* had developed resistance to the benzimidazole-DPA combination. Grey mould is still controlled by the benzimidazole-DPA combination, presumably because this pathogen does not recycle on field bins as readily as does *P. expansum*, and it has therefore been subjected to less selection pressure for fungicide resistance (Rosenberger, 1990). Captan (N-trichloromethylthio-4-cyclohexene-1,2-dicarboximide; Captan 50W, Captan 80W, Captec 4L) has a postharvest registration but has proved to be only moderately effective for controlling *P. expansum* and *B. cinerea*. Captan residues are not acceptable in some markets.

Much effort has been devoted to the development of biocontrols for postharvest diseases of apples (Janisiewicz, 1998), but, while many of the biocontrol agents selected and developed to date have proved to be very effective in controlled tests, commercialization of biocontrols has been slow. Reasons

may include limited markets compared with field crops, liabilities associated with the value of the stored crop, a high public profile for apples in debates relating to food-safety issues and difficulties in devising shelf-stable formulations of biocontrol agents (Watkins *et al.*, 2003). Moreover, biocontrols generally cannot currently provide eradicant activity against established infections. Using combinations of biocontrols and reduced rates of TBZ may be more effective than using either product alone (Chand-Goyal and Spotts, 1997). When such combinations are used, the chemical fungicide may provide eradicant and short-term protectant activity necessary to prevent decay until the biocontrol agents become established in wounds or other infection sites.

Regardless of the postharvest fungicide or biocontrol, good sanitation will remain essential for reducing inoculum on contaminated field bins and in packing-houses and storage rooms. Badly contaminated bins should be cleaned and disinfested (steam-cleaned) before they are reused for a new crop. Plastic bins may carry less inoculum than wooden bins (D A. Rosenberger, Hudson Valley Laboratory, Cornell University, 2001, personal communication) and also have the advantage of reducing bruising and abrasion where apples contact the sides of bins. Careful fruit handling, rapid cooling after harvest and storage at recommended temperatures also help to limit the development of postharvest decay.

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24 Production and Handling Techniques for Processing Apples

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24.1 Introduction

Much attention is paid to the production practices devoted to fresh-market apples.

However, in many areas more apples are processed than are sold as fresh fruit. In the USA, recent statistics from the US Department of Agriculture (USDA) indicate

that, in the last 5 years, approximately 40% of all the apples grown in the USA are processed (Evans, 2000). In 1999, approximately 2.2 million t were processed out of a total crop of 5.3 million t. The era of the most rapid growth in apple processing in the USA was the period from the end of the Second World War in 1945 until the early 1970s (O'Rourke, 1994). This time period coincided with a trend where the American family moved away from the traditional life styles of a single-wage-earner household to a dual income with less time spent on food preparation. However, in the 1970s, changes in dietary patterns led to a decline in the consumption of processed fruits and vegetables. In general, the processing industry has been geographically tied to locations where there were ample local supplies of apples.

24.2 Processed Products

24.2.1 Juice

Apple-processing products are varied and depend upon the state or country and the economic status of the area. The primary processing product produced in the world is apple juice. Apple juice is a clarified product that is pasteurized to make it shelf-stable. In international trade, apple juice is usually concentrated to 70° Brix or higher to reduce

shipping large volumes of water. The product is reconstituted for packaging and sale to the consumer.

Estimated 1999/2000 world production in selected countries is believed to be 633,000 t, (70/71° Brix), 7% below the previous season's output (Rosa, 2000). The downturn mainly reflected decreases in both Polish and Argentine production. Production in the USA, the world's largest apple-juice concentrate (AJC) producer and consumer, was estimated to increase to 150,000 t.

Apple juice is produced in many countries. Five European countries account for trade of approximately 521,000 t year⁻¹ (Neubert and Lee, 1999). This quantity includes both production and refiltration of juice initially produced in other countries. These countries are mainly exporters, consuming only 35% of the traded product and exporting the remainder. Poland, Italy and Germany were the top three European AJC-exporting countries in 1998, according to the Food and Agriculture Organization (FAO) (Table 24.1). Germany is a major producer of AJC, producing 73,872 t in 1997/98 (Luetzenkirchen and Frimmersdorf, 1998). In Poland, approximately 60% of the apples produced are processed. Processed products include AJC, fruit beverage, wine and jam. Germany is the leading destination for Polish AJC, accounting for more than 80% of the total AJC exports. The German AJC

Table 24.1. Top ten concentrated-apple-juice exporting and importing countries in 1998 (t) (from the Food and Agriculture Organization of the United Nations available at <http://apps.fao.org/>). Production from the Peoples' Republic of China is not included in this summary

Exports			Imports		
Rank	Country	Volume	Rank	Country	Volume
1	Poland	104,497	1	USA	219,971
2	Italy	79,392	2	Germany	123,665
3	Germany	73,397	3	UK	35,913
4	Austria	58,253	4	Italy	33,227
5	Argentina	54,732	5	Austria	22,566
6	Turkey	51,275	6	The Netherlands	16,203
7	Chile	33,756	7	Canada	14,856
8	USA	25,005	8	Belgium-Luxemburg	10,754
9	Moldova, Republic of	18,630	9	Denmark	6,640
10	Switzerland	9,060	10	France	6,295
Total all FAO member nations		551,853	Total all FAO member nations		515,203

Table 24.2. Five-year US fresh and processed apple production ('000 t) (from Fruit and Tree Nuts, FTS-290, National Agricultural Statistics Service, USDA)

Year	Total production	Fresh market	Total processed	Juice and cider	Tinned	Frozen	Dried	Other	Per cent processed
1995	4519.3	2649.1	1870.2	1150.3	586.0	138.3	151.4	35.4	41.4
1996	4829.3	2815.4	2013.9	990.3	587.0	121.5	143.6	27.8	41.7
1997	4610.6	2637.4	1973.1	973.0	679.9	158.3	121.1	81.6	42.8
1998	4916.9	2908.7	2008.3	1127.3	532.4	120.7	149.6	43.1	40.8
1999	4713.6	2705.3	2008.3	1115.8	611.6	97.7	126.2	57.1	42.6

industry also depends on supplies from Italy. Other significant sources include Turkey, the Czech Republic and Moldova. The USA remains the largest single export market for German AJC, while the USA and Germany were the top importing countries. Most commercial apple cultivars will produce an acceptable juice if they are blended. The quality and taste of the juice, however, is directly related to the cultivar and maturity of the fruit. Hazy or cloudy AJC is often the result of high levels of starch in the fruit from being harvested too early. Juice from less developed countries may be cloudy due to their inability to provide adequate filtration and/or heating (Neubert and Lee, 1999).

In the USA approximately 54% of the processed fruit is made into juice (Table 24.2), followed by tinned, frozen, dried and other uses. On a local basis, in nearly every state of the USA, small apples and those not meeting fresh-market standards are processed into fresh non-pasteurized juice, which is typically referred to as sweet or fresh cider. This cider is sold locally by the farmer or to local stores. It must be refrigerated and has a shelf-life of no more than 2–3 weeks.

Recently, regulations have been proposed by the Food and Drug Administration of the USA that will mandate pasteurization for all juice producers that sell cider to wholesale markets. Under the regulations, juice processors must develop and implement a hazard analysis and critical control point (HACCP) plan that includes control measures sufficient to achieve a 5-log (99.999%) reduction in harmful pathogens. Producers that sell directly to the consumer will not have to pasteurize but will have to place a warning label on their containers indicating that the product was not pasteurized.

24.2.2 Cider

Sweet cider is not to be confused with the fermented cider that is produced predominantly outside the USA. Fermented cider is a shelf-stable product that has been fermented to increase the alcohol content and is typically sold in restaurants or pubs. In the USA it is generally known as hard cider.

Outside the USA, 'cider' is the fermented juice of the apple and has been known for centuries. Its production and use probably originated in the Trans-Caucasus region. Cider spread through the Greek and Roman worlds, but the product was not as popular as wine. Eventually it became associated with the more northern regions of Europe, where grapes were not as successful. The major cider-making areas now are England, north-western France, Spain, Germany and Switzerland. The industry has grown in these areas partly as a tourist attraction, with 'Routes des cidres' being developed similarly to the wine industry (Rowles, 2000). The major production areas in the UK are Hereford, Somerset, Devon, Avon, Norfolk and Sussex. Recently in the USA, there has been an increase in cider production, with the product being marketed to a specific age-group (Rowles, 2000).

Traditionally, apples grown for cider were produced on standard trees in small orchards with the grass under the trees being grazed by livestock as part of a mixed self-sufficient farm (Williams, 1992). There was minimal management or pest control and fruit may have been harvested from the tree or gathered from the ground. Traditional orchards planted on seedling rootstocks have slowly been replaced with more intensively managed semi-intensive orchards in recent years. Recent production figures compiled by the Ministry of Agriculture, Forestry and Fisheries in the UK indicate that average production for 1996–1999 was around 75,000 t and that the average price was around US\$141 t⁻¹ (Lawton, 2000) on an estimated area of 5043 ha.

Cider apples are distinct cultivars and are chosen for their fruit qualities (Table 24.3). The cultivars can be classified into four groups: (i) sweet – low both in tannin (0.2%) and in acidity (<0.45%); (ii) bitter-sweet – high in tannin (>0.2%) but low in acidity; (iii) bitter-sharp – high in both tannin and acidity; and (iv) sharp – low in tannin, high in acidity. Tannin level is often regarded as the distinguishing feature of cider apples. It gives the fresh fruit a bitter and astringent taste. Tannins also help prevent breakdown of the apple pulp during processing and

Table 24.3. Cider-apple cultivars grown in the UK by taste group.

Bitter-sweet	Sharp
'Ashton Bitter'	'Backwell Red'
'Ashton Brown Jersey'	'Bramley's Seedling'
'Bals Bittersweet'	'Brown's Apple'
'Belle Fille De La Manche'	'Cider Lady's Finger'
'Black Dabinett'	'Crimson King'
'Brimley Bittersweet'	'Frederick'
'Brown Snout'	'Improved Lambrook Pippin'
'Brown Thorn'	'Reinette O'bry'
'Bulmers' Norman'	'Severn Bank'
'Burrowhill Early'	'Stembridge Cluster'
'Chisel Jersey'	'Tom Putt'
'Coat Jersey'	
'Collington B g Bitters'	
'Dabinett'	
'Doux Normandie'	
'Dove'	
'Dymock Red'	
'Elys Bitter'	
'FillBarrel'	
'Harry Masters Jersey'	
'Improved Dove'	
'Major'	
'Maundy'	
'Medaille D'or'	
'Michelin'	
'Muscadet De Dieppe'	
'Nehou'	
'Omont'	
'Osier'	
'Perthyre'	
'Reine De Hatives'	
'Reine des Pommes'	
'Rougette Douce'	
'Somerset Redstreak'	
'Stable Jersey'	
'Stembridge Jersey'	
'Tard ve Forestiere'	
'Tremlett's Bitter'	
'Vagon Archer'	
'Vileberie'	
'White Jersey'	
'White Norman'	
'Yarlington Mill'	
	Sweet
	'Court Royal'
	'Dunkerton Late Sweet'
	'La Bret'
	'Morgan Sweet'
	'Northwood'
	'Sweet Alford'
	'Sweet Coppin'
	'Tall Sweet'
	'Taylors'
	Bitter-sharp
	'Breakwell's Seedling'
	'Broxwood Foxwhelp'
	'Foxwelp'
	'Genet Moyle'
	'Improved Redsteak'
	'Kingston Black'
	'Porter's Perfection'
	'Red Foxwhelp'
	'Stoke Red'

makes it easier to press cider cultivars than fresh-market cultivars.

24.2.3 Apple sauce

Apple sauce is a uniquely North American product. A mixture of cultivars is usually used to achieve a consistent and uniform

product. Apple sauce is produced by peeling and coring the fruit and then slicing them into small irregular pieces, to which sugar or maize syrup may or may not be added. The mixture is then precooked, usually by passing through a pressurized steam tunnel for 4–5 min until the mixture temperature reaches about 96°C. Once the fruit is cooked, it is passed through a finishing machine that

regulates the sauce grain and removes any large coarse materials. If the sauce is placed directly into tins and the mixture temperature is maintained at 93°C, no further cooking is needed. If the temperature of the mixture drops, however, then another cooking step is needed to kill any pathogens that may be present.

Processors look for specific characteristics in apples, such as Brix (11–24°), sugar : acid ratios (25–60), aroma, yellow or white flesh, variable grain or texture and good water-holding capacity. Cultivars with high water-holding capacity allow the addition of water to increase the yield of the end-product. The US standards for grade of tinned apple sauce are based upon five attributes: colour, consistency, absence of defects, flavour and finish. Finish is primarily due to the size and distribution of the apple tissue in the sauce, which is cultivar-dependent (Nogueira *et al.*, 1985).

24.2.4 Slices and whole apples

Another product is the production of whole baked and sliced apples. These are often processed in tins and utilized in pie fillings. Slice packs generally consist of a single cultivar and are therefore not blended. Trim waste must be minimal and firmness and texture are important qualities for cultivars destined for this product. Uniformity of size, shape and core diameter are important to obtain maximum yield when fruit are mechanically peeled and cored. The apple slices can also be further processed by dehydrating and freezing. In recent years, small local processing operations have been established to supply nearby bakeries for pastry uses. Apples destined for sauces and slices receive a higher premium than those processed into juice.

Other products are made depending upon the individual processor's ability to diversify his/her product line. Apple butter, spiced apple rings and apple jelly are considered speciality products made from apples and constitute less than 1% of total products produced (Root, 1996).

24.3 Supply

In the eastern USA (primarily Pennsylvania, Virginia, West Virginia, New York and Michigan), apples grown for processing are utilized for apple slices, apple sauce, whole baked apples, spiced apple rings and apple juice. The processing industry developed in these states as the market for processed products expanded and as growers increased production (Plate 24.1).

In the western USA (primarily Washington, Oregon and California), apples are diverted into processing uses as a result of fruit not meeting fresh-market quality standards. About 20–30% of the apples end up at processing plants (Hansen, 1997). Few growers in the Pacific north-west region are growing specifically for processing. While the majority of fruit ends up in juice, some higher-quality fruit may be utilized for other products. Typical cultivars utilized include 'Golden Delicious', 'Granny Smith', 'Rome Beauty', 'Winesap', 'Gala' and 'Fuji'. Processors in Washington look for fruit that is a minimum of 64 mm in diameter. Premiums are sometimes paid for internal-quality parameters, such as high acid. Prices fluctuate depending upon supply and demand. In the eastern USA, prices are usually set at the beginning of the season. An economic disadvantage for Pacific north-west growers is the added cost for storage.

In Canada, Nova Scotia's processing industry is closely aligned with a specific bakery company that prefers 'Northern Spy' apples. The remainder of the processed production consists of packing-house fruit that did not meet fresh standards and a small hard-cider industry in eastern Canada. In British Columbia, a single company dominates the processing market and products are primarily made from fruit that did not meet fresh-market standards (Advanced Resource Consulting Ltd, 1999).

While the tonnage of processed apples is high, the value of the crop is not necessarily on a par with fresh-fruit uses. In 1998, the estimated value of apples was just over US\$1.3 billion, of which US\$1.1 billion was for fresh fruit and only US\$0.2 billion was attributed to processed fruit (Evans, 2000).

24.4 Processing Industry in the People's Republic of China (PRC)

In recent years, apple production in the PRC has dramatically increased. Acreage in the country is estimated to be around 2.44 million ha (Rutledge, 2000). It is estimated that only about 5–10% of each year's apple crop is processed, the dominant product being juice or juice concentrate. While 'Fuji' is the most important apple cultivar grown in the PRC, the cultivar 'Qinguan' is the most popular among the country's AJC producers. The rise in apple-juice production is largely a result of foreign joint-venture investments with companies such as Dole/Tropicana, Great Lakes, Kirin and Ronghzi. These companies buy local deciduous fruit to manufacture into juice for the domestic market. Total AJC produced in 1998 was 90,900 t and utilized 900,000 t of apples (4.6% of the total crop). In 1999, this increased to 153,059 t. The majority of the juice that was exported went to Japan and Europe.

It is believed that there are approximately 55 processing plants in the country, with the largest number in the Shandong (22 plants) and Shaanxi (17 plants) provinces. Unlike the industry in the USA, the juice production in the PRC is seasonal, starting in August and running until about January or February, when the supply runs out. Apples are not stored for later use. The amount of juice produced is expected to continue to increase for the short term, as only 60–70% of the PRC's apple trees are bearing.

24.5 Important Processing Cultivars

All apple cultivars grown can be used to some extent for processing. However, there are certain characteristics that make some cultivars more desirable for different end-products. Cultivars used for processing vary by region. The large mid-Atlantic region, which encompasses the states of Pennsylvania, West Virginia, Maryland and Virginia, primarily utilizes 'York Imperial', 'Golden Delicious' and 'Rome Beauty' for processing. Other cultivars that processors utilize include 'Granny Smith', 'Winesap'

and, in recent years, 'Fuji'. The New York processing industry is based upon 'McIntosh', 'Rhode Island Greening', 'Wayne' and 'Northern Spy' (S. Hoying, New York, USA, 2000, personal communication).

The Michigan processing industry breaks their processing cultivars down into three categories (D. Ricks, Michigan, USA, 2000, personal communication). At the extremes are those grown only for processing and those that are grown only for fresh-market consumption. In between are the dual-purpose cultivars that can be grown for either the fresh or the processing market. The cultivars grown primarily for processing include 'Northern Spy', 'Winesap', 'Rhode Island Greening' and 'Mutsu'. The dual-purpose cultivars are 'Jonathan', 'Golden Delicious', 'Rome Beauty', 'Idared' and 'Jonagold'. Processed products from these two categories include apple sauce, tinned apple slices, frozen slices and pie filling. The fresh-market cultivars can also be diverted into processing, but, as in the western USA, these are primarily packing-house culls that are made into juice. Culls are fruit that are unmarketable due to small size or quality defects, such as poor colour and disease and insect damage.

In eastern European countries, such as Poland, older cultivars, such as 'Antonovka', 'McIntosh' and cultivars of local importance, dominate the processing market. Other cultivars recommended in Poland include 'Landsberge', 'Wealthy', 'Golden Delicious', 'Idared' and 'Warta' (A. Czynczyk, Skierniowice, Poland, 2000, personal communication). Most of the dominant processing cultivars developed as chance seedlings. In the USA many of the prominent processing cultivars are also among the leading cultivars in production (Table 24.4).

24.5.1 'York Imperial'

'York Imperial' was a chance seedling found in York, Pennsylvania. It was discovered when schoolboys passing by a seedling tree in late March picked up the dropped fruit and found how firm the fruit remained (Rollins, 1989). It is a late-maturing cultivar,

Table 24.4. US apple production by cultivar ('000 t) (from US Apple Association)

Cultivar	1995	1996	1997	1998	1999	2000 forecast
'Delicious'	1910	1982	1720	2084	1575	1701
'Golden Delicious'	673	680	653	757	625	674
'Fuji' ^a	197	248	300	394	312	388
'Granny Smith' ^a	272	312	310	359	370	374
'Gala' ^a	125	159	181	233	275	308
'Rome Beauty'	334	257	276	265	272	250
'McIntosh'	248	212	259	198	281	214
'Jonathan'	142	87	104	114	126	101
'York Imperial'	106	78	87	71	98	88
'Idared'	107	75	96	98	113	88
'Empire'	83	83	95	82	102	82
'Cortland'	50	47	49	45	56	44
'Rhode Island Greening'	62	46	43	42	49	40
'Newtown'	65	58	56	54	32	35
'Stayman'	41	27	31	30	34	30
'Northern Spy'	43	25	35	35	50	29
'Winesap'	33	14	18	18	19	13
'Gravenstein'	18	9	9	8	4	4
All others	291	312	361	397	408	381
Total ^b	4801	4709	4683	5283	4800	4843

^a Includes only western production. Eastern and mid-west production is included in 'all others'

^b Sum of cultivars may not add to total due to rounding of individual cultivars.

being harvested approximately 170–180 days after full bloom. The fruit are characterized as being firm to hard, with a creamy-yellow flesh. The firmness and colour of the fruit provide superior processed sliced products that hold their shape. 'York Imperial' has a long storage life and is resistant to bruising. The fruit has a high water-holding capacity, which results in a high processing yield for sauce. Disadvantages of the cultivar include its lopsided shape, which can affect the peeling process, and a lack of aroma. Culturally, the tree is vigorous, with a tendency to biennial bearing and a propensity to develop calcium deficiency-related disorders, such as cork spot and bitter pit.

24.5.2 'Golden Delicious'

'Golden Delicious' was a chance seedling found in West Virginia in the USA on the Andrew Mullins farm (Maas, 1970). It is not related to the 'Delicious' cultivar, other than both being commercialized by Stark Brothers

Nursery. 'Golden Delicious' fruit are regarded as being sweet and semi-firm and they store well and are non-browning when cut. The fruit is harvested 135–150 days after full bloom. Horticulturally the tree is classified as an easy tree to prune and train. It is rated as very good to excellent for most processed products (Way and McLellan, 1989). One of its major advantages is its versatility in making processed products and its ability to be blended with other cultivars to improve the uniformity of the finished product.

24.5.3 'Rome Beauty'

'Rome Beauty' was discovered as a sucker growing from below a graft union in the early 1800s in Ohio in the USA. It has become the fifth most popular cultivar in the USA. Its major advantage is good adaptation to a wide range of growing conditions, heavy annual bearing, large fruit size and late bloom. When young, the tree has an

upright growing habit, which gradually develops into an acrotonic growth habit as it matures. The fruit can be used either fresh or for processing, although neither is of high quality. It is less desirable for apple sauce than most cultivars, because of poor flesh colour (Way and McLellan, 1989). Fruit matures approximately 165–170 days after full bloom but can hang longer on the tree. Storage life is very good. Its best processing use is in the making of whole baked-apple products. ‘Lawspur’ and other high-colouring red strains of ‘Rome Beauty’ are somewhat less desirable for use in processing, because of the tendency for the development of red coloration in the flesh of the fruit

24.5.4 ‘McIntosh’

‘McIntosh’ was discovered by John McIntosh in about 1811 in Dundela, Ontario, in Canada, but it was not until about 1900 that the cultivar became widely known (Upshall, 1970). ‘McIntosh’ fruit ripen 120–135 days after full bloom and the cultivar is considered an annual bearer. It is known to be a cold-hardy cultivar, having survived cold winters when ‘Baldwin’ trees were killed. Today ‘McIntosh’ is the seventh most widely grown cultivar in the USA. It is also popular in eastern European countries, such as Poland. The flesh of ‘McIntosh’ is distinctively white and produces a whitish-coloured processed product. ‘McIntosh’ is in many cases grown as a fresh fruit cultivar and fruit that do not meet fresh-market standards are diverted into processing.

24.5.5 ‘Northern Spy’

‘Northern Spy’ was a chance seedling found in approximately 1800 in western New York in the USA, but it was not until about 1840 that it was recognized outside its small area of origin. Fruit from ‘Northern Spy’ ripen approximately 150–160 days after full bloom. The fruit are large and distinctly ribbed. The best processed products produced from the fruit include slices, either tinned or frozen, and whole baked apples. The major advan-

tages of the cultivar are the large fruit size, yellow flesh colour, flavour and late-blooming tendency. Disadvantages of ‘Northern Spy’ are its extreme lack of precocity and its vigorous growth and biennial-bearing tendency. Use of dwarfing rootstocks is mandatory to reduce the growth and lack of early production.

24.5.6 ‘Idared’

‘Idared’ was produced by a cross made in Idaho of ‘Jonathan’ × ‘Wagener’ in 1942. It is a dual-purpose fruit, being grown for both the fresh and the processed markets. The bright, shiny, red fruit ripen 145–160 days after full bloom. The major advantages of this cultivar are its large round fruit, precocity and long storage life. Disadvantages include the tree susceptibility to both fire blight (*Erwinia amylovora* (Burr.) Winslow *et al.*) and powdery mildew (*Podosphaera leucotricha* (Ell. & Ev.) E.S. Salmon).

24.5.7 ‘Jonathan’

‘Jonathan’ is believed to be a chance seedling of ‘Esopus Spitzenberg’ found in Kingston, New York, around 1825 (Larsen, 1970). It is well adapted to the eastern and midwestern regions of the USA as well as central Europe, although its production has declined compared with previous years. It is, however, still widely grown for processing in Michigan. Apple sauce made with ‘Jonathan’ has a good texture and an appealing yellow colour. Small fruit size is a drawback, resulting in less efficiency for mechanical peelers and higher trim and core waste. The tree is very susceptible to fire blight, powdery mildew and cedar apple rust (*Gymnosporangium juniperi-virginianae* L.).

24.5.8 Other cultivars

Cultivars of lesser importance include ‘Gravenstein’, grown primarily in California and producing an excellent product for apple sauce and pie filling. ‘Rhode Island

'Greening' is an old cultivar that is still produced in New York and Michigan but is losing favour. It is commonly known as 'Greening' and, as the name implies, is green in colour when harvested for processing. Apple sauce made with this cultivar has a high yield due to its high water-holding capacity. 'Granny Smith' is a chance seedling from Australia that in recent years has been increasingly used for processed products. The late-harvested fruit make excellent pie fillings. 'Twenty-Ounce' is a large-fruited cultivar that is produced in New York but with declining production. Way and McLellan (1989) indicate that it can be used without blending for sauce and that it has a high yield due to its large fruit size. Other cultivars that are used for processing include 'Mutsu', 'Jonagold', 'Monroe' and 'Stayman'. With the exception of 'Monroe', processing is usually a secondary market, as these cultivars all have a higher fresh-market value.

24.6 Fruit Attributes

The quality of the fruit delivered to the processor ultimately affects the quality of the end-product. LaBelle (1981) has described the important quality characteristics of the raw product that are desired by the processors. Factors that have an impact on the end-product include ripeness, bruising, decay, soluble solids, flesh colour, total solids, total acid, pH, organic flavour compounds, tannins and juiciness. Specific attributes may be more or less important, depending upon the intended product. For baked apples, firmness, damage and core size are important, while, for sliced apples, damage and core size are less important. Fruit size and core size have an impact on the product yield and hence the profitability of the processor. Therefore, the larger the fruit diameter, the fewer units of fruit that have to be peeled to produce a given amount of useful flesh. It takes 45–64 mm (2½ in.) apples to produce 10 lb of slices, while it takes only 26–76 mm (3 in.) apples to make 4.5 kg (10 lb.) of slices. Therefore, an apple that is approximately 64 mm has only 51.3% of its flesh that is used to make slices, while a

76 mm apple has 60% of the fruit that can be converted into slices (Cooper, 1988).

24.6.1 Maturity

Soft fruit do not withstand the rigours of mechanical peeling, cooking and thermal processing as well as firmer fruit. Overripe fruit also do not have as high a juice yield as firm mature fruit. Less mature fruit will produce a grainy sauce, which is a positive aspect (Lanza and Kramer, 1967).

24.6.2 External appearance

Generally speaking, apples destined for processing do not need to meet the same appearance standards as those established for fresh-market fruit. Colour, which is an important grade factor for fresh fruit, is less important. Red skin, however, can limit use in processing when the skin colour 'bleeds' into the flesh of the fruit. This is particularly true with certain strains of the cultivar 'Rome Beauty'. Further complicating the process is the fact that red anthocyanin pigments are unstable and turn brown during long-term storage of tinned products, rendering them unusable for producing a pink sauce or juice (LaBelle, 1981).

24.6.3 Flesh colour

The flesh colour of apples varies by cultivar and age of fruit. The flesh of immature fruit may have a distinct green tinge, while over-mature fruit may be deep yellow. The individual preference of the processor for the end-product colour can dictate the cultivar preference for that processor. Certain companies produce a more yellow sauce, while others prefer a whiter or cream-coloured sauce.

24.6.4 Fruit firmness

Fruit firmness is one of the major criteria utilized by classifiers at the receiving station to

determine the immediate placement of the fruit. The firmest fruit are usually directed towards long-term controlled-atmosphere (CA) storage, while the softest fruit can be directed into immediate use in the processing plant. Fruit firmness also influences the final product that is to be made from the fruit. Apples destined to be processed into tinned slices or pie filling must be firmer than those to be used for sauce or juice. Minimum firmness for slices is 53 N (12 lb.) – less than this and the slices will not retain their integrity after cooking.

24.6.5 Damage and decay

Fruit that has an excessive amount of bruising, hail damage, corking or insect feeding is downgraded during inspection. Most processors list bruising as the biggest single problem. Apart from direct fruit damage from insect feeding, there may also be an impact upon processor returns. Hull and Rajotte (1988) showed that fruit placed in storage with damage from insect feeding tended to have an increased susceptibility to fungal disorders and to a shortened storage life. The damaged fruit were still classified as US No. 1 and therefore did not have an impact on the fruit grower's financial return but would have had an effect upon the flexibility of use and yield for the processor.

24.7 Differences in Cultural Practices

Cultural practices for growing processing apples are not very different from practices utilized for fresh-market apples. In the case of fruit that is directed to the processor as a salvage from fresh fruit, there would be no differences in their cultural practices since the fruit utilized is the result of off-grade or poorer quality fruit that was initially intended for the fresh market.

Fruit that is grown intentionally for the processor does have a few changes in cultural practices, but not as many changes as one would expect. As mentioned previously, the processors pay a premium for larger-sized fruit that have a minimal amount of bruising

and defects. Light exposure is still important to ensure adequate flower formation and return bloom, and the trees therefore need to have a fairly open structure. However, in many instances the pruning is not as detailed as is demanded by fresh-market standards, since fruit colour at harvest is not a criterion for payment. Good processing growers try to perform some pruning in all their blocks each year, but may only do a more detailed pruning every 2–3 years. In older orchard blocks on seedling rootstocks, it was common to establish tree height by using tree-topping equipment. This may or may not be followed up in the same year with a few detailed cuts. Harper (2000) estimated costs for pruning large, standard, processing trees on a per-tree basis to be US\$4.00–5.00, due primarily to the large tree size.

The conversion to high-density plantings on dwarfing rootstocks for processing orchards has not been as rapid as the conversion in fresh-market orchards. The slow conversion is probably due to three factors. First, many of the established processing orchards are old and were established many years before a great variety of dwarfing rootstocks were available. It is not unusual to have processing orchards that are in excess of 35 years old. Secondly, since external fruit appearance is not as critical, the need for small, compact, tree canopies that produce high-coloured fruit is not as great as in fresh-market production systems. In a 10-year study of 'York Imperial' on seven different rootstocks, Greene *et al* (1997) found that total cumulative yield for the years 1991–1996 (fifth to tenth year) varied from 85.6 to 125.3 t ha⁻¹. Early in the life of the orchard, it appeared that some of the smaller trees had higher yield efficiencies than some of the larger trees. Thirdly, there has not been the need to change to new, higher-value, apple cultivars. An advantage that the processing grower has is the stability of the cultivars. Much of today's change in apple systems is predicated on the need to plant new cultivars that bring a high price in the market, hence the need to continually replant to stay current with market pressures. Processing orchards do not need to replace cultivars and therefore can have a longer lifespan.

The number of pesticide applications is only slightly lower for processed fruit, but there is less concern about fruit finish and the materials utilized may be less expensive. Economic injury thresholds are higher.

Fertilization practices may be different in orchards where the fruit is grown for processing. Since payment is based upon fruit size and total weight, the fruit grower may frequently apply a higher rate of nitrogen to the trees in an attempt to increase fruit size. Increasing nitrogen does have a detrimental affect upon fruit firmness, colour and storability, but these factors may not have an impact on the overall grower return.

The major difference in cultural practices between fruit grown for processing and that grown for the fresh market is in the use of special growth-regulator sprays. Where fresh-market fruit may be treated with gibberellins to increase fruit size and fruit length-to-diameter ratio, it would not be economically justified to do the same on processing cultivars. Nevertheless, many fruit that are diverted to the processor due to inferior quality may have been treated if the remainder of the crop had been destined for the fresh market.

Production costs for orchards that grow

fruit strictly for processing are estimated to be approximately US\$740 ha⁻¹ cheaper than the costs of production for fresh-market apples (Table 24.5). The budget was based upon a mature orchard at a density of 190 trees ha⁻¹ (6.0 m × 8.5 m) as compared with a fresh market orchard at 672 trees ha⁻¹ (3.0 m × 4.9 m). These costs are not based on a specific orchard but are meant to be generalized estimates based on grower and university personnel input. Potential returns are lower due to the lower prices paid for processed fruit. Prices quoted by processors (Table 24.6) can vary, depending upon supply and demand and the world price for apple concentrate. Harvest costs are estimated at US\$1.35 per bushel (19 kg unit). Fruit grown specifically for processing do not require the added cost of grading and packing that is required for fresh-market fruit (Crassweller, 1995).

24.8 Harvest and Handling Techniques

Processing companies require a consistent supply of good-quality fruit. Fruit must be free of insect larvae. At inspection, there is zero tolerance for insects and any amount

Table 24.5. Mature processing apple orchard budget, 77 trees acre⁻¹ (190 trees ha⁻¹), Pennsylvania, 1998. Estimated operation and input costs per acre (US\$).

Operation	Month performed	Tractors and equipment	Labour	Materials or service	Total costs
Pruning and training	February	—	308.00	—	308.00
Liming	February	—	—	12.50	12.50
Applying herbicides	March	1.72	3.12	12.63	17.46
Fertilizing	May	2.10	1.00	23.90	27.00
Bee rental	May	—	—	25.00	25.00
Chemical thinning	May	1.87	1.98	17.25	21.10
Mowing	Season (× 5)	22.65	18.95	—	41.60
Applying pesticides	Season (× 12)	22.44	23.76	456.18	502.38
Mouse control	November	2.10	1.00	10.00	13.10
Totals		52.88	357.81	557.46	968.15
Interest on operating capital	—	—	—	—	46.25
Land charge	—	—	—	—	150.00
Total specified costs					1164.40

Table 24.6. Returns above specified growing and harvesting costs under various price and yield combinations (US\$).

Orchard block price ^a (US\$ bu ⁻¹)	Yield					
	200 bu acre ⁻¹	400 bu acre ⁻¹	600 bu acre ⁻¹	800 bu acre ⁻¹	1000 bu acre ⁻¹	1200 bu acre ⁻¹
1.50	(1114)	(1064)	(1014)	(964)	(914)	(864)
2.00	(1014)	(864)	(714)	(564)	(414)	(264)
2.50	(914)	(664)	(414)	(164)	86	336
3.00	(814)	(464)	(114)	236	586	936
3.50	(714)	(264)	186	636	1086	1536
4.00	(614)	(64)	486	1036	1586	2136
4.50	(514)	136	786	1436	2086	2736
5.00	(414)	336	1086	1836	2586	3336
5.50	(314)	536	1386	2236	3086	3936

Values in parentheses indicate returns below production costs.

^a Picked in bins in orchard. Average price received for all apples (US\$).

bu, bushel

found by the inspector will automatically cause the entire load to be rejected. The biggest single problem processing companies have is bruised fruit (Cooper, 1988). Most processing companies now operate 12 months a year and therefore utilize CA storage. Bruised apples have a shorter storage life and companies may, therefore, pay a premium for fruit with lower amounts of bruising. Growers are continually cautioned that they should not have two different picking standards for fresh and processing fruit. The USDA grade allows for no more than 10% bruising. Due to the need for minimal bruised fruit, machine harvesting of fruit has not been developed. There is interest in utilizing machines if one can be developed that can minimize bruising. Currently in the USA, most fruit are harvested by hand and placed into large wooden bulk bins, which typically hold 20–25 bushels (381–476 kg). The fruit are then loaded by fork-lift on to flat-bed trucks for transportation directly to the processing receiving station. Williams and Copas (1992), however, indicate that there are several types of mechanical harvesters in England for cider-apple production. These include 'shake-and-catch' machines and sweepers that remove fruit from the orchard. When using mechanical harvesting equipment, it becomes more important that the orchard floor is well managed. Management includes the proper levelling and mowing of

the sod, as well as choosing slow-growing grass species.

24.9 Delivery to the Processing Plant

Figure 24.1 is a general flow diagram of how a processing plant might receive, categorize and inspect and grade apples. At the processing plant, the truck is first driven to a check-in station and weighed (Fig. 24.2). The next step is a subjective sampling, where a quality-control person collects small subsamples to measure fruit maturity and to check for major quality defects. This is done to determine how long the fruit can be stored (Fig. 24.3). The maturity of the fruit is typically evaluated based on fruit firmness, starch rating, visual inspection and, in some cases, internal ethylene. Based upon the results of these tests, the fruit may then be designated for immediate processing (most mature), regular cold storage or long-term CA storage. Each bin is labelled with a barcode, which contains information about the grower, results from the maturity tests and the cultivar name (Fig. 24.4).

The next step is the inspection to determine the grade and size distribution of the entire lot, which will be used for payment. In the USA, grades utilized can be either USDA grades or other grades agreed to by the processor and grower. A random sample of

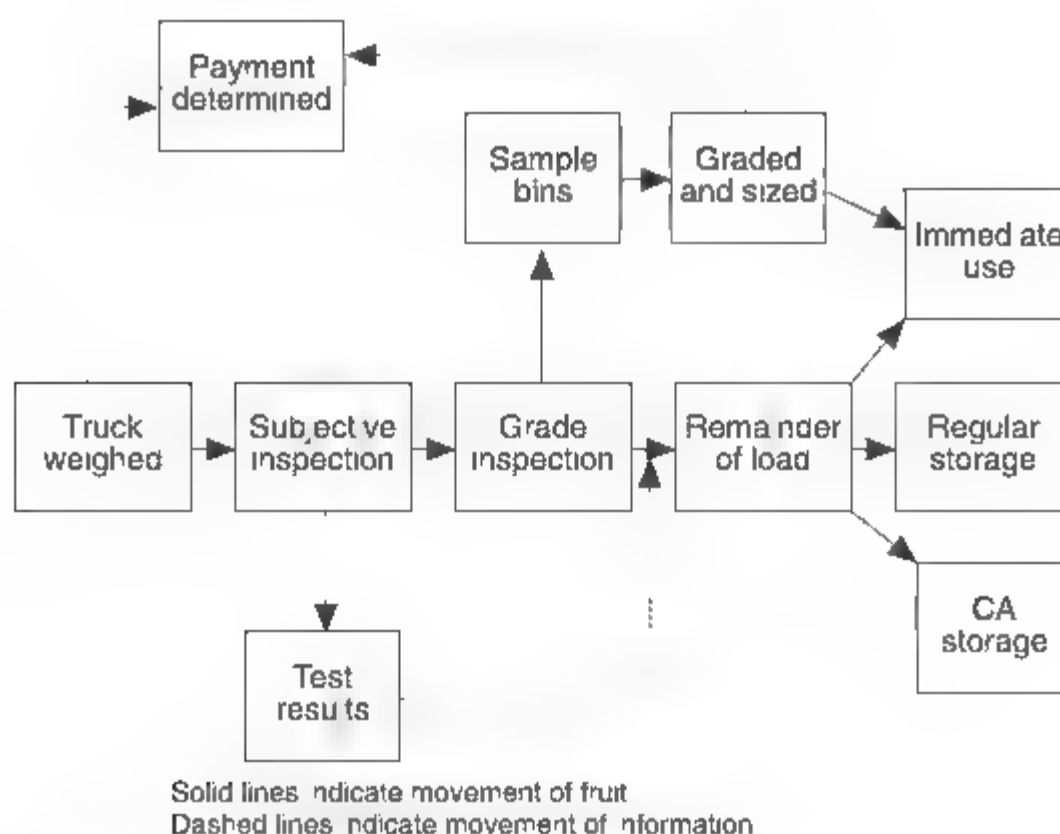


Fig. 24.1. Flow diagram of a typical fruit-receiving process at a processing plant.



Fig. 24.2. The trucks with loaded bins are driven over a scale to determine the weight of the fruit being delivered and then the truck is weighed after the bins are unloaded

bins is chosen, based upon a random-number generator and the total number of bins on the truck. These bins are removed for grading. There is no one established method for collecting a sample from the bins, due to the different nature of the processing plants. However, it is the responsibility of the person or agency assigned to conduct the inspections to collect a good representative sample of the lot.

Bins are taken to an inspection station. At the inspection station several methods may be used to collect a random sub-sample of the

fruit from the bins. In some instances, the entire bin is dumped over a sizer with a gap cut to drop out randomly a sample of fruit. In another system, the bin is covered with a corner that has a square 30 cm × 30 cm hole. When the bin is inverted, the apples from the uncovered area drop out to be graded. The location of the uncovered square is varied with each bin. Some processing companies may secure the sample with a butterfly net or scoop as the fruit is being unloaded directly into the plant in the water flume. Still other



Fig. 24.3. At a substation, fruit are selected randomly for measuring firmness. Brix and starch to determine potential storage life



Fig. 24.4. Each bin on the truck is tagged with the grower information (a) The individual tag shows a bar-code, cultivar, starch reading, Brix and fruit firmness (b)



Fig. 24.5. An inspector collects a sub-sample of fruit to be used to determine fruit grade for payment.

companies collect a sample by hand by digging into the bin to remove fruit (Fig. 24.5).

The sub-sample that is collected is then examined by an inspector (Fig. 24.6). The individual is usually hired by an independent organization run by federal and state government, growers and processors. The inspector is paid by the processing company. Apples are first inspected and all culls and juice apples are removed from the sample and weighed, all weights being recorded to the nearest whole pound (i.e. 0.45 kg). Depending upon the processor and the supply and demand for apples, apples in the US No. 2 grade may also be removed and weighed at this time. Apples are examined

for the presence of insect larvae during the initial inspection.

The remaining apples (US No. 1 grade) are graded into sizes based upon the minimum diameter of the fruit, regardless of its stem or calyx position (Fig. 24.7). The following sizes and criteria are used as outlined in the USDA Inspection Guidelines: (i) under 2½ in. (under 57 mm); (ii) 2½–2¾ in. (57–64 mm); (iii) 2¾–3 in. (64–75 mm); and (iv) 3 in. and up (≥ 76 mm). Fruit in each size category is then weighed. The percentages of the different grades and sizes are calculated on the basis of the total weight of the sample. These percentages are then recorded and applied to the weight of the entire truck-load to determine the return



Fig. 24.6. An initial inspection of fruit done where ciders, culls and No. 2 grades are removed.



Fig. 24.7. At the final inspection the remaining No. 1 grades are graded into sizes and the percentage in each is determined and is used to determine payment to the grower.

the grower will receive. The payment for the apples is based on the size, grade and quality, at the discretion of the buyer.

24.10 Grade Interpretations for Payment

The USDA Standards for Grades of Apples for Processing in the USA are based primarily on the amount of 'trim waste' occurring during 'the usual commercial preparation for use'. 'Commercial preparation' presumes the use of power-peeling machines, followed by any necessary hand-trimming. Trim waste is described as the amount of the fruit that would need to be removed due to damage or decay. The inspector must use considerable judgement as to the percentage of fruit flesh that needs to be removed (Anon., 1986). As a general policy, in removing bruises or shallow defects, a rounded or curved cut should be used. For injuries that penetrate deep into the flesh, a cone-shaped cut should be employed. US No. 1 and US No. 2 grades differ from each other based upon the percentage of trim waste. Primary components that affect trim waste include the amount of bruising, fruit decay and insect damage.

Apples containing any insect larvae or holes indicating larvae entry are not allowed in any grades. In recent years, the presence

of these holes has been enough for processing companies to reject entire loads of fruit. However, damage by surface-feeding insects that do not penetrate into the fruit is graded on trim waste. Studies have shown that apples damaged by surface-feeding insects, such as tufted apple bud-moth (*Platynota idaeusalis* (Walker)), lost more weight in storage and did not store as well as uninjured fruit (Hull and Rajotte, 1988). Since the grower is paid on the initial weight at the time of inspection, the loss in weight and shorter storage life are an unrecoverable loss to the processing company. Bruising is scored on a trim-waste basis and varies depending on grade requirements. As mentioned previously, growers must judiciously work with their harvest crews to minimize the amount of bruising that occurs during the harvest. Firmness is an important attribute that determines the potential storage life, as well as the possible end-product. The higher-value products require the firmest fruit.

The inspector is also responsible for correctly identifying the cultivar that is delivered. In the case of mixed cultivars, a lot may be certified as such when designated by the processor/grower contract. When lots are not designated as 'mixed cultivar' and do contain two or more cultivars, the inspection is based on predominant cultivar.

The USDA grade standards do not set the price for the fruit, and individual processing companies may have more or fewer price categories. Some processors have developed their own requirements, based upon their needs. Processors that make products other than juice realize the importance of fruit size and its impact upon the efficiency of the peeling operation. Individual processing companies may impose additional standards on the fruit. The processors may pay an additional premium for fruit that meet minimum standards, as a means of enticing growers to produce fruit of the quality desired by the processor.

24.11 Future Directions of the Industry

A greater emphasis on delivering large bruise-free fruit will become more important in the

future. The ability to store fruit for 12 months will mean that fruit coming out of storage must be of sufficient quality to be utilized for any product that is needed. Processing companies cannot afford to store fruit for an extended period of time if they come out of storage suitable only for making juice.

The development of preharvest and storage technologies such as the use of aminoethoxyvinylglycine (AVG) and 1-methylcyclopropene (MCP) will provide the ability to increase the number of cultivars for processing use. Cultivars that previously had a short storage life may now be utilized due to increased storability. Current cultivars utilized can come out of storage with higher quality and provide greater flexibility in how the fruit may be utilized. Processing companies will need to provide sufficient incentives for growers to produce cultivars and grades of fruit that are most profitable for both the orchardist and the processor.

Undoubtedly, there will be an even greater emphasis on reducing pesticide applications for the production of processing apples. There is potential for the use of apple-scab (*Venturia inaequalis* (Cooke) Wint.)-resistant cultivars. Greater emphasis on the quality of fresh fruit will mean that growers will no longer be economically able to divert low-quality fresh-market apples into the processing market as a cost-effective technique. The quality demands for high-quality processing and for fresh-market apples are becoming so different that fruit will no longer be able to be diverted from one outlet to the other.

The reduction in trade barriers will increase the world movement of apple products, particularly AJC. The development of free-market economies in eastern Europe and western Asia have the potential to further increase the production of AJC. Unfortunately, in the short run, the overproduction of AJC from these areas will only serve further to depress world apple prices. Initial entry into the world markets of AJC from countries such as the PRC have had an impact on world AJC prices. In the future, higher-value products, such as apple sauce or sliced apples, may enter world trade. The world demand, however, may limit the quantity that can be profitably sold. Rising energy costs will have a direct impact upon the trade and profitability of processed products. A budget analysis indicated that transportation costs is a major factor that affects interregional competition within a country (Jordan, 1983). We can assume that world markets will be similarly affected by transportation costs between different countries.

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